WOOD DENSITY STUDIES IN *PINUS RADIATA* D. DON.

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ORIGINALITY OF THE THESIS

The work described in this thesis is entirely my own, apart from section 2.2, which is based on a joint paper by myself and Drs P. Rudman and M. Higgs published in the Journal of the Institute of Wood Science (Appendix III). My part in this joint work consisted of extraction of most of the basic data, the calculations dealing with film variability and some sections of the draft of the paper.

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ABSTRACT

The X-ray densitometric technique has been used to study the variation in several parameters of wood density of *P. radiata* under the influence of fertiliser application, site quality, and water availability.

Methods of sampling wood properties were examined in small and large trees. In small trees sampling at a percentile height was found preferable to sampling at a fixed height above ground, but in large trees sampling at breast height was just as efficient as percentile sampling. To compare wood properties at multiple points in the stem it is essential to sample at comparable growth stages from the apex of the tree.

Ranked-set sampling, a technique not used previously for sampling wood properties, has been used to estimate average stand wood density at breast height. It is simple and objective, providing an unbiased estimate of the population mean from a minimal sample size.

Weighted whole tree density of 14-year old trees was shown to be strongly inversely correlated with tree vigour and stem taper. The strength of these correlations was greater on higher quality sites.

The influence of site quality on wood density was studied on two soil types in the one plantation. At age 14 site index did not affect weighted average density at breast height but density was markedly lower on one soil type than on the other. Analysis of ring-by-ring trends in mean density revealed an inverse site index : wood density relationship developing with increasing age of trees on one soil type only.

Fertilisation was found to have a considerable effect on wood density. The results of four studies in stands ranging in age from seven to 20 years may be summarised as follows:

(a) Both earlywood and latewood growth were stimulated by fertilisation, but earlywood was always stimulated to a greater extent, resulting in a decrease in latewood percentage and mean density.

(b) Fertilisation increased the within-ring density range, usually by a reduction in minimum density in the ring, but sometimes by a combined increase in maximum density.

(c) The effect of fertiliser on wood properties was greatest in the lower bole, decreasing progressively up the bole and becoming negligible at the top.

(d) A combined NPK fertiliser caused a highly significant increase in stem taper and a marked change in the breast height-whole tree relationship.

(e) Fertilisation accentuated the development of subsidiary peaks on the density curves ("false rings").

(f) Specific nutrient elements have been shown to influence density in different ways. There may be an influence on wood density without an associated growth response.

(g) The fertilised trees had a more gradual gradient in mean density from the pith outwards.

(h) Initial wood density of a tree did not influence the magnitude of its response in density following fertilisation.

(i) All sizes of trees in a stand responded to fertilisation in the same way.

(j) The duration of a wood density response exceeded the period of study in all four experiments.

Evidence has been presented to show how the magnitude of the effect of a particular fertiliser on wood properties is determined by the balance of available nutrients.

The influence of water availability on wood formation is the same at all points on the stem in P. radiata. Sheath average density could be related to the seasonal variation in moisture availability.

The density of the expanding xylem was estimated at weekly intervals throughout the 1962-63 growing season in four sample trees. Soil moisture storage for the same weeks was estimated by a computer simulation technique. Moisture availability has a dominating influence on wood density for most of the growing season in southern Australia. Other factors such as temperature, daylength and solar insolation are probably more important at the beginning and the end of the growing season.

In all four sample trees density decreased markedly one week after relief of drought by heavy mid-summer rains, thus confirming that cells in the expanding layer during drought periods retained the capacity for expansion to large diameter earlywood-type cells. It was determined that lumen diameter is the major component of wood density in P. radiata. The importance of double wall thickness as a component of density varied among the four sample trees.

The significance of the results has been discussed in relation to forest management and utilisation. It was concluded the changes in wood density resulting from cultural practices such as fertilisation are no greater than the natural variation in these properties and will not affect the utilisation of the species.

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CHAPTER 1

INTRODUCTION

1.1 General.

Pinus radiata D. Don is one of the most important exotic conifers in the world. Man-made forests of the species now exceed 2,500,000 acres (1,000,000 hectares) in Australia, New Zealand, South Africa, Chile and Spain. This area is being expanded at a rapid rate. Australia alone intends to increase its area of softwood plantations to 3,000,000 acres by the year 2000, the bulk of this expansion being in *P. radiata*. The reasons for the widespread use of the species are its exceptional productivity, ease of propagation, its suitability for temperate sub-humid climates and the general utility of its timber.

The species is managed under intensive systems of silviculture, usually in even-aged stands established by planting. It has often been planted on soils of low fertility status, particularly where the economics of transport dictate that the crop be situated within a certain radius of a main market. The addition of mineral fertilisers has been found desirable or even necessary on such soils. The planned rate of planting of *P. radiata* over the next 30 years will mean that a large proportion of this area will be grown on soil types requiring fertiliser application to achieve satisfactory development. Furthermore, it is expected that widespread fertilisation will be necessary to alleviate the observed decline in productivity in second rotation stands and that there will be a trend for the use of fertiliser even on good sites (Gentle and Humphreys, 1967).

Thinning of plantations has always been practised extensively in Australia. Since about 1950, influenced by the work of Craib in South Africa, management has been inclined toward heavier thinning schedules and, in some instances, intensive pruning operations.

There is evidence for several other conifers that all the abovementioned cultural operations have an influence on wood properties, but there has never been a systematic attempt to quantify any such influence on P. radiata.

The current trend toward earlier harvesting of the crop increases the significance of any changes in wood properties wrought by management practices. Whereas it has previously been generally accepted that the rotation length for the species would be 40 years, there is now growing pressure to shorten the rotation to the vicinity of 25 years, partly due to the changing requirements of wood using industries (Anon, 1970) and partly because increasing attention is being paid to the economics of growing trees (Sinden, 1968). It is therefore more important than ever before to have quantitative information on the effects on wood properties of any management action.

In recent years the need for the large wood using industries to increase efficiency through a more precise knowledge of their raw material combined with their widespread involvement in tree breeding programs has stimulated much research on wood quality. Considerable progress has been made in recent years in relating wood and fibre properties to pulp characteristics. Blending of wood from different areas to achieve the optimum furnish is commonplace.

An example of the industrial significance of a relatively small change in wood density was given by Mitchell (1964). A fall of 0.02 gm./cc. in density was equivalent to a fall of 100 lb. dry weight per cord (or 125 lb. per cunit of 100 cu. ft.). Such a change is important to the pulp industry because of the associated higher logging and digester costs for the same pulp yield. Density changes affect the sawn timber industry also, since the same fall in density will result in a fall of approximately five percent in the modulus of rupture (Sangüesa, 1965).

Because of its high growth rate and rapid response to changes in environmental conditions, any changes in wood properties due to management methods might be of greater importance in *P. radiata* than in the slower growing Northern Hemisphere conifers from which most of our present information has been gained. These same characteristics of the species also make it a very useful research tool. It is an exotic with a very restricted original seed source and so the complicating factor of geographic races in a natural population does not exist.

1.2 Evaluation of Wood Quality.

The term "wood quality" can be extended to cover many properties of wood such as branch size, angle and frequency (and whether they are live or dead), incidence of reaction wood, ring width, chemical composition, wood density, cell wall thickness, lumen diameter, tracheid length, grain angle, and shrinkage, to mention but a few.

There is, unfortunately, no absolute index of wood quality, the relative importance of any of these properties depending very much on the user. The situation is further complicated by fundamental differences in wood anatomy between gymnosperms and angiosperms. In this study the problem is approached from the viewpoint of intrinsic properties of wood and that for conifers only.

The basic cause of variation in wood quality is variation in the attributes of the individual conifer tracheids. Disregarding aspects of cellular ultrastructure, which are beyond the scope of this study, the significant cell attributes are lumen diameter and wall thickness. Within any one annual ring of a conifer there are generally two distinct zones characterised by differences in these parameters. In the early part of each growing season the cell diameter is relatively high and cell wall thickness is low (earlywood or springwood); at some point during the course of the season there is a transition, which may be gradual or abrupt, to reduced cell diameter and increased wall thickness (latewood or summerwood). Wood density in these two zones is low and high respectively, in more or less direct proportion to the changes in cell attributes (if cell wall extractives are ignored). All measures of intrinsic wood quality attempt, in some way, to summarise this variation in tracheid characteristics.

The proportion of higher density wood in a ring is frequently used as an index of wood quality being known as latewood percentage or summerwood percentage. Both terms are misleading, implying that high density wood is formed in the summer or late in the growing season. As will be demonstrated in this study this is certainly not so for *P. radiata*, it being possible for the lowest density in a ring to be recorded during the summer under suitable growing conditions. For lack of more suitable terms, earlywood and latewood have been used here to denote the relatively low density and high density sections of the ring respectively.

Latewood percentage has the valuable advantage of being simple to measure, but, because of the difficulty of fixing the transition from earlywood to latewood, precision is often questionable. The point of transition is often fixed purely subjectively on the basis of the colour change going into the high density phase. It is also demarcated on the basis of cell dimensions, although not entirely successfully. Because of these difficulties latewood percentage has tended to fall into disfavour in recent years, but if it can be precisely defined and objectively assessed the concept is still a useful one.

The most widely used index of wood quality is density or specific gravity. The two terms are equivalent in the metric system, which is used here wherever possible. For convenience density has been used throughout the present study even when the author of a paper being cited has used specific gravity.

The reason for the popularity of wood density as a measure of wood quality is its relative ease of measurement and its strong correlation with commercially important wood characteristics. It is, for example, closely related to timber strength and working properties, shrinkage, pulp yield and (for some processes) pulp quality. Since it is the sum of cell diameter, cell wall thickness and extractive content (where applicable), it is a useful guide to these more fundamental characteristics also. Because of this all-round usefulness, density has been used extensively in the present study.

1.3 Techniques.

Apart from any effects due to cultural treatments or factors of the site, wood density has been shown to be strongly influenced by cambial age. In most conifers density usually increases from the pith outward, reaching a more or less constant value after the juvenile phase of growth, and within any growth sheath density increases from apex to base. Many workers in this field have failed to make allowance for these systematic patterns of variation. Indeed Göhre (1958) was of the opinion that much of the confusion in the literature on the variation of wood density with site quality was due to poor sampling methods. A major consideration in the present study was the use of biologically sound methods of sampling.

In addition to the sampling problem at the individual tree level, there has been little attention given to the development of objective, statistically sound procedures for the estimation of average wood density of a stand. Most studies comparing wood density in different stands have used sampling methods such as "only the best dominant trees", or "trees from the dominant and codominant classes only". In the present study a sampling procedure not previously used in wood quality research is described and tested on an investigation of the variation in wood density due to site quality.

Most studies of wood density have reported their findings in terms of average density over a set number of rings of an increment core or as average density of complete sample discs or parts of discs. Such data, while still useful, does not permit detailed quantitative examination of any treatment effects. For this purpose data at the intra-increment level are necessary, and whereas the conventional methods of determination of density can be adapted for the purpose, their use is tedious in the extreme.

Several new techniques have been developed in recent years to meet this situation. The X-ray densitometric technique developed in France by Polge was selected as the most promising both as regards precision and versatility. Considerable developmental work needed to be done before the technique was suitable for routine use.

In addition to the conventional parameters of mean ring density and latewood percentage the technique allows the measurement of maximum and minimum density in a ring and therefore of the range in density, or texture, of the wood. The continuous record of wood density throughout the growing season offers the possibility of studying the effect of environmental factors on wood properties and of a convenient method of investigating some physiological responses of trees to their environment.

1.4 Aims of the Study.

(a) to investigate the application of X-ray densitometry to wood quality research, and in particular to the study of variation of wood density within the annual ring of P. radiata,

(b) an investigation of the variation in wood density over a range of site quality in one plantation area of P. radiata, and

(c) to investigate the influence of some inorganic fertilisers on wood properties of P. radiata.

1.5 Conventions Used in This Thesis.

For uniformity of presentation and the elimination of unnecessary repetition the following conventions are used throughout this thesis :

(a) Whenever a figure for density is quoted, it is given in gm./cc. and the units usually will not be quoted in the text.

(b) In tables of analysis of variance or in tables listing correlation coefficients, statistical significance at the 5.0 percent level will be represented by *, at the 1.0 percent level by **, and at the 0.1 percent level by ***. Statistical non-significance will be denoted by N.S.

(c) Spelling follows the advice of the Style Manual, Commonwealth Government Printing Office, Canberra, 1966.

CHAPTER 2

TECHNIQUES AND METHODS

2.1 Review of Available Techniques.

In recent years there has been increasing emphasis on the need to study wood properties at the intra-increment level. Existing methods available for wood density measurement were unsuited to this study. This encouraged the development of a number of indirect methods for measuring wood density either continuously or at close intervals across the ring. Conventional methods were also developed further to measure density on very small specimens but will not be considered here.

A microphotometric method was developed in Canada (Green and Worrall, 1964) which produced a computer tape record of cell wall area and distribution from measurements of relative transmission of light through a stained microtome wood section. The data could then be converted as wood density and latewood percentage. This technique has since been developed further to use reflected light and so is able to scan smoothed increment cores or wood discs directly (Besley, 1969). If this latest modification gives good results it would probably be the cheapest method of obtaining a continuous record of wood density variation.

Three different radiation techniques have been used for the determination of wood density - beta-ray (Cameron, Berry and Phillips 1959), gamma-ray (e.g. Jurasek and

Jokel, 1963), and X-ray (Polge, 1963, 1965a, 1966). The principle of both the beta-ray and gamma-ray methods is that for a sample of uniform thickness and moisture content the amount of radiation absorbed is directly proportional to the density of the wood.

Beta-rays are of relatively low penetrating power, depending on the isotope used, and are suitable for a range of sample thickness from thick microtome sections (using Carbon-14) up to about 12mm. (using Strontium-90). The wood sample is passed between the beta-ray source and a scintillation probe, the variations in the particle count rate being converted, by appropriate instrumentation, to a continuous record of wood density variation.

Gamma-rays have higher penetrating power than beta-rays so are suitable for use with thicker specimens. For example Loos (1961), with Lead-210 as the source, used wood specimens 6cm. in thickness. The gamma-ray technique is not widely used as yet, but may receive more attention in the future because of its relative portability and suitability for large timber sizes.

In the X-ray technique the wood samples are X-rayed and variations in optical density of the sample image on the film translated to a continuous recording of wood density by a double beam recording microdensitometer. Over a range of wood density from approximately 0.2 to 0.9 gm./cc. the relationship between wood density and optical density is almost linear for "soft", or low energy, X-radiation. The underlying theory has been outlined by Polge (1965a). The sample thickness can be varied in the range 4 - 10mm. and the samples can be increment cores or specimens machined to a standard thickness out of larger blocks.

The beta-ray (Strontium-90) and X-ray techniques have been compared by Harris and Polge (1967) who concluded that, overall, there was good agreement between them. A comparison of the beta-ray and X-ray density tracings of the same sample presented in this paper shows that the beta-ray method was incapable of resolving the within-ring patterns of density variation. However, it appears better results may be obtained with a Carbon-14 source and microtome sections (Phillips, 1968). There is considerable advantage in being able to use machined wood samples or increment cores. Small deviations in sample thickness from the nominal size are less significant and localised variations in density are integrated. The microdensitometer has greater resolving power due to the smaller size of the scanning beam - 0.05mm. x 1.0mm., compared with the 0.5mm. x 2.0mm. beam of beta particles (Harris and Polge loc. cit.)

The X-ray densitometric technique is considered to be superior for detailed work and for this reason it has been used exclusively in the present study.

2.2 Quantitative Determination of Wood Density by X-ray Densitometry.

General.

When X-rays are produced by the projection of electrons onto an anode the spectrum of radiation produced has a peak emission wavelength which varies inversely with the voltage applied. When wood is irradiated at low voltage the longer wavelength radiation in the spectrum is selectively absorbed, resulting in a non-linear relationship between wood density and optical density. Linearity of the relationship can be improved by passing the X-ray beam through an aluminium screen (0.6mm. thickness), so attentuating the longer wavelengths and reducing the width of the radiation spectrum. Since image resolution is greater at the longer wavelengths, X-ray densitometry involves a compromise between image sharpness and linearity of the wood density: optical density calibration curve. In addition to the purity of the emission spectrum, the voltage used affects the exposure time for a film of given speed rating.

For the determination of wood density the following information is required:

(i) the voltage which gives the best compromise between the conflicting requirements outlined above

(ii) the time necessary for correct exposure of a given film

(iii) a calibration curve to relate optical density of the X-ray image to wood density.

The calibration curve was derived by relating the optical density of a large number of standard wood samples to their known gravimetric density. In addition, working standards were prepared for routine work since it would be impractical to X-ray these standard wood samples on every film used. Cellulose acetate was chosen as a suitable material and was calibrated in terms of wood density for various thicknesses using the curve established for the standard wood samples. These cellulose acetate working standards are referred to as step wedges and the term step refers to an individual level of a step wedge.

Calibration.

Thirty-four wood blocks including diverse softwood and hardwood species were selected to give a wide range of wood density. From each block was sawn a sample 10mm. x 10mm. x 50mm. carefully oriented in the radial and longtitudinal directions. The samples were conditioned to 8 $\pm$ 0.05 percent moisture content (m.c.) in a glass desiccator over a saturated solution of sodium dichromate which has a relatively constant aqueous vapour pressure at ambient temperatures. The conditioned samples were machined on the four faces to a final cross section of 6.90 $\pm$ 0.05mm. using a Black and Decker router modified to work as a spindle moulder. The ends of each sample were smoothed with a plane. This sample thickness was used throughout this investigation. The figure of 6.9mm. is an arbitrary one chosen because samples of about 5mm. thickness shattered easily in some hardwood species.

Gravimetric density of each sample was based on oven dry weight and its volume at eight percent m.c. calculated from micrometer measurements.

Cellulose acetate sheet, 0.8mm. in thickness, was cut into seven strips approximately 7cm. in width and in lengths varying from 1cm. to 7cm. in steps of 1cm. After dipping the strips in acetone they were pressed together forming a step wedge in which thickness increased progressively from 0.8mm. to 5.6mm. This large step wedge was then sawn into six replicates, each 1 cm. in width.

The standard wood samples and the step wedges were placed on top of 10in. x 8in. X-ray film, care being taken that no sample or wedge was closer than 3 - 4cm. from the film edge. Previous experience had shown that a band around the edge of the film of that width differed in optical density from the remainder of the film, possibly receiving greater development due to penetration of developer along the film edge as well as through the film surface.

The X-ray source was situated overhead, 2.5 metres from the film, in order to ensure parallel radiation at the film surface (Polge, 1965a).

Initially a voltage of 15Kv was used, as suggested by Polge, but the resulting non-linearity of the wood density : optical density relationship was too great to obtain accurate results (Fig. 2-1). Subsequently a voltage of 23Kv at 20ma was used for an exposure time which varied according to film speed.

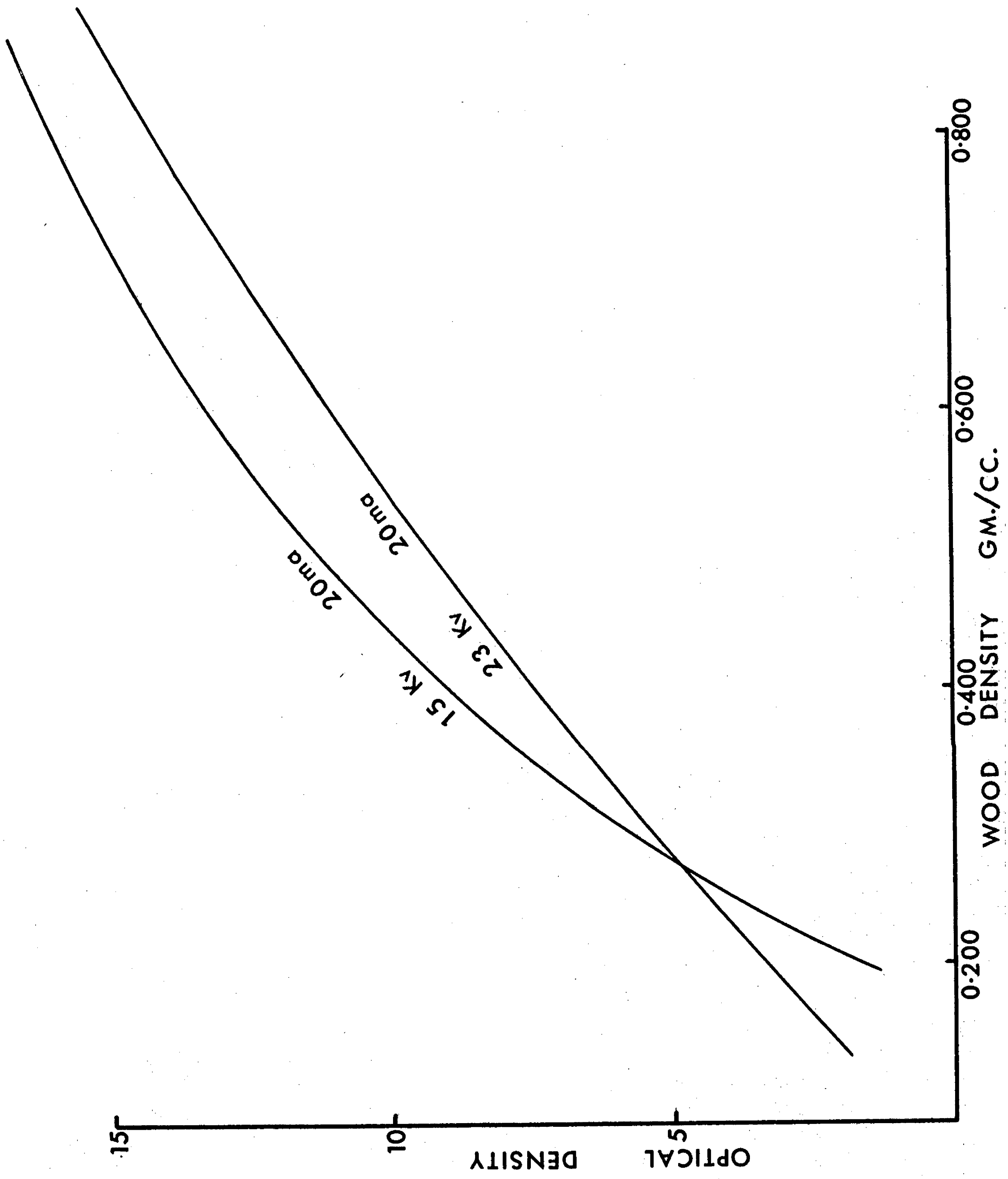
Each film was developed individually for 5 minutes, fixed for 5 minutes, both with continuous agitation, and then washed thoroughly and dried rapidly.

The optical contrast of the images on the films was translated into a continuous chart recording with a Joyce Loebl Mark IIIcs microdensitometer. From an arbitrary baseline fixed for each film the optical density of a sample or wedge was measured as its mean linear displacement. Two traverses with slight lateral displacement were made over the length of the standard wood samples and the step wedges. Optical density was recorded as the mean of these two traverses and for the samples a linear correction was applied for any slight deviations from 6.9mm. thickness.

Results and Discussion.

The relationship between wood density (Ygm/cc.) and optical density (Dcm.) for all observations was described by both linear and curvilinear regression (Fig. 2-2). The observations showed no consistent behaviour by softwood or

FIG. 2-1 Effect of voltage on linearity of the calibration curve.



hardwood species, but some aberrant samples exerted a strong influence on the error of each regression. Consequently the linear and curvilinear regressions were recalculated using only those observations within the wood density range 0.25 to 0.90gm./cc. Each regression with its error mean square (EMS) is shown in Table 2-1; the curvilinear regression is an improvement over linear regression of 30 percent for all wood samples and 20 percent for the selected samples.

TABLE 2-1 Wood density: optical density regressions

Regression (a)	Error Mean Square	LSD. gm./cc. (b)
1. Linear (all observations)		
$Y = 0.0638 + 0.0735D$	0.0013	0.055
2. Linear (selected observations)		
$Y = 0.0964 + 0.0679D$	0.0006	0.039
3. Curvilinear (all observations)		
$Y = 0.1660 + 0.0439D + 0.0018D^2$	0.0010	0.049
4. Curvilinear (selected observations)		
$Y = 0.1897 + 0.0388D + 0.0020D^2$	0.0005	0.036

Note: (a) Y represents wood density, D optical density of the X-ray negative

(b) $LSD = [2\ (\text{optical density S.E.})^2 + \text{Error Mean Square}]^{\frac{1}{2}}$

The wood density values assumed for the steps of the step wedges were derived from the curvilinear regression based on all observations. The values for steps 2 to 7 were respectively 0.229, 0.344, 0.468, 0.592, 0.717 and 0.867gm./cc.

Tests with step wedges on films of several different commercial brands showed important differences in background variability. When optical densities of wedges were corrected for variations in background, corresponding steps were found to be almost identical between films, but the extra time required to make the correction is prohibitive for routine work. Only one brand of film was considered suitable for routine use without background correction. This brand (Kodak AA) was investigated more extensively and all data quoted in this investigation refer to this brand only. Exposure time at 23Kv and 20ma was seven minutes.

The standard deviations in terms of wood density for six steps on six test films are presented in Table 2-2 and the analysis of variance in Table 2-3. From Table 2-2 the film mean standard deviation (over all steps of the wedges) ranges from 0.003 for film 131 to 0.009 for film 65. Similarly, the mean standard deviation for each step ranges from 0.007 for step 7 (0.867) to 0.005 for step 3 (0.344), there being some indication of a linear trend. Within the limits of wood density from 0.344 to 0.867 the coefficients of variation range from 0.8 to 1.5 percent of the density value.

TABLE 2-2 Standard deviations of wedge steps between films and within films

Density Level	Film No. 63	65	72	131	132	133	Mean S.D.	C.V. %	S.E.
0.867	0.007	0.009	0.008	0.007	0.006	0.007	0.007	0.80	0.0146
0.717	0.004	0.011	0.007	0.004	0.007	0.005	0.006	0.83	0.0126
0.592	0.003	0.010	0.008	0.004	0.006	0.003	0.006	1.00	0.0114
0.468	0.006	0.011	0.008	0.002	0.005	0.002	0.006	1.29	0.0114
0.344	0.012	0.004	0.007	0.001	0.005	0.002	0.005	1.50	0.0104
0.229	0.011	0.008	0.005	0.002	0.005	0.002	0.006	2.56	0.0110
Mean S.D.	0.007	0.009	0.007	0.003	0.006	0.003	0.006		
S.E.		0.0176					0.012		

TABLE 2-3 Analysis of variance

Source of Variation	D.F.	S.S.	M.S.	V.R.
Within film	5	0.000147	0.000029	5.34**
Within wedge	5	0.000018	0.000004	N.S.
Error	25	0.000138	0.000005	
Total	35	0.000303		

Analysis of variance indicates that some films are significantly more variable in optical density than others but that between films there are no consistent differences in optical density variability for any wedge step.

The least significant difference (LSD) is composed of two parts, one due to the error associated with the film variability and the other to error in deriving the calibration curve.

$$LSD = [2(\text{film optical density standard error})^2 + (\text{calibration curve standard error})^2]^{\frac{1}{2}}$$

ie. $LSD = [2(0.012)^2 + EMS]^{\frac{1}{2}}$

where the LSD ranges from 0.036 to 0.055 (Table 2-1). The EMS will exert a considerably greater influence on the LSD than the optical density standard error of 0.012. It is for this reason that the brand of film investigated, despite a low magnitude but highly significant variability between films, is considered acceptable for general work. For between species comparisons the greatest gains in using the technique are likely to accrue from a reduction in the error component of the calibration curve.

It will be noted that the above holds only when it is desired to make an absolute estimate of wood density. For within species comparisons it does not matter if the estimates of density are all biased to the same extent, so that the error due to the calibration curve can be deleted from the above equation, which then becomes :

$$LSD = [2(0.012)^2]^{\frac{1}{2}}$$
$$= 0.0054 \text{ gm./cc.}$$

which is a negligibly small figure.

The following procedures were adopted to keep errors associated with the technique below this level.

1. Samples were not placed closer than 4cm. to any edge of an X-ray film.

2. Two step wedges were placed in amongst the wood samples on every film; if the variation between their optical densities was greater than 1mm. (on the densitometer tracings) at the 0.468 density level, the film was discarded and the samples X-rayed again. In early work two films in every five had to be discarded, but improvement in development techniques reduced the discard rate to less than one in five.

3. A calibration curve was prepared for each accepted film. This enabled variation in the arbitrary baseline between films to minimise measurements on the tracings, but for each film the position of the baseline relative to the levels of the wedge steps was constant on all tracings made from it. This film calibration curve also had the effect of accounting for any variation from the standard calibration curve due to differences in degree of film development. These deviations were, however, found to be extremely small. The film calibration curve used the standard wedge values as Y-ordinates and the height intercepts of each of the steps above the baseline as the X-ordinates.

2.3 Some Practical Considerations in X-ray Densitometry.

The microdensitometer produces a chart of the continuous variation in wood density across a sample. In order to use this record it is necessary to decide:

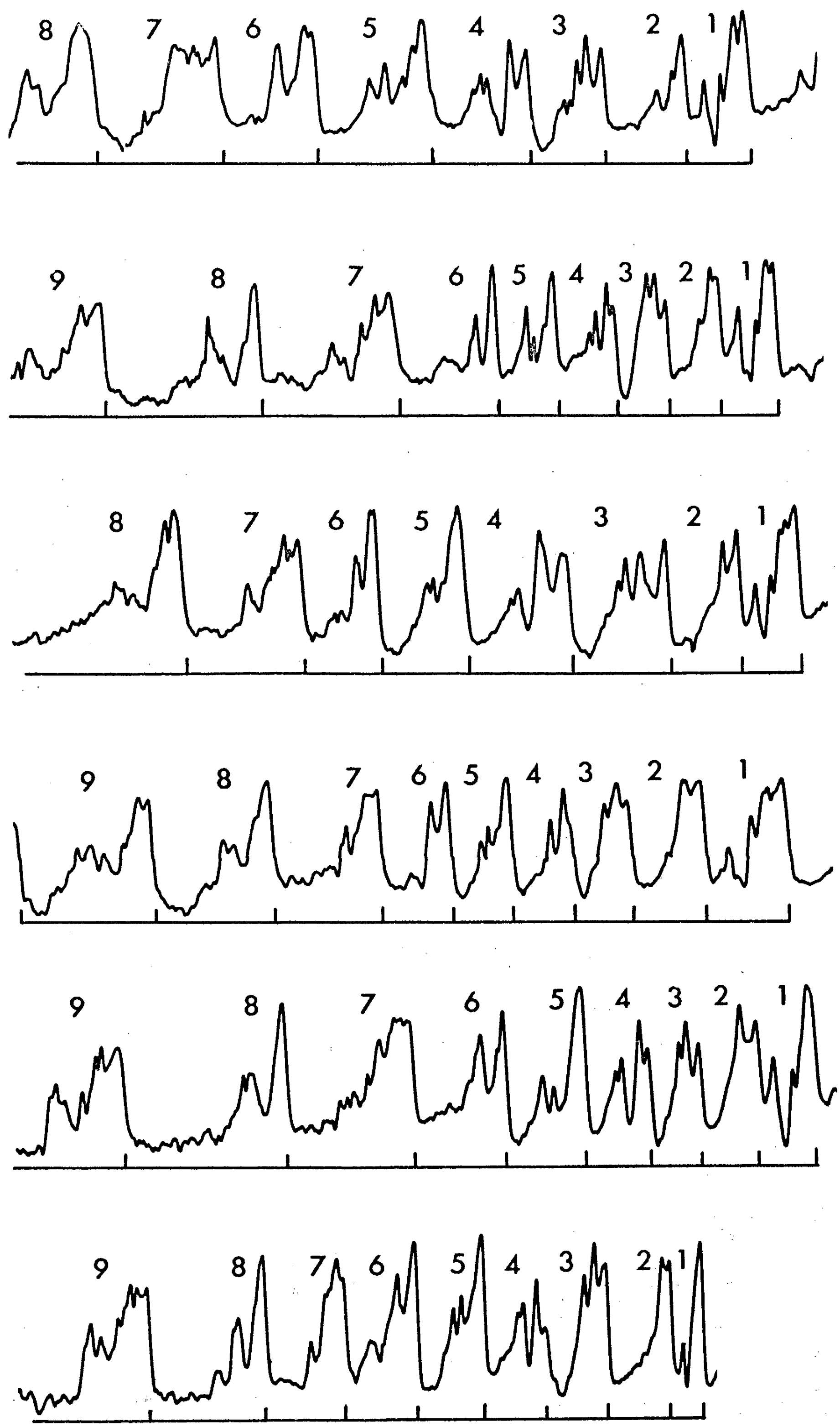
(i) how to define the annual rings

(ii) what parameters to measure on the tracings.

Definition of the Annual Ring.

On the densitometric tracings the transition from one growth ring to another is typically an almost vertical fall in the density curve. The convention adopted here is that the season's ring begins just as the density tracing begins to curve away from the vertical. Fig. 2-3 shows part of the tracings for six different trees from the main study area. The horizontal line under each of the tracings marks off each annual increment and the numbers above the tracings

FIG. 2-3 Typical density curves - Flynn Creek.

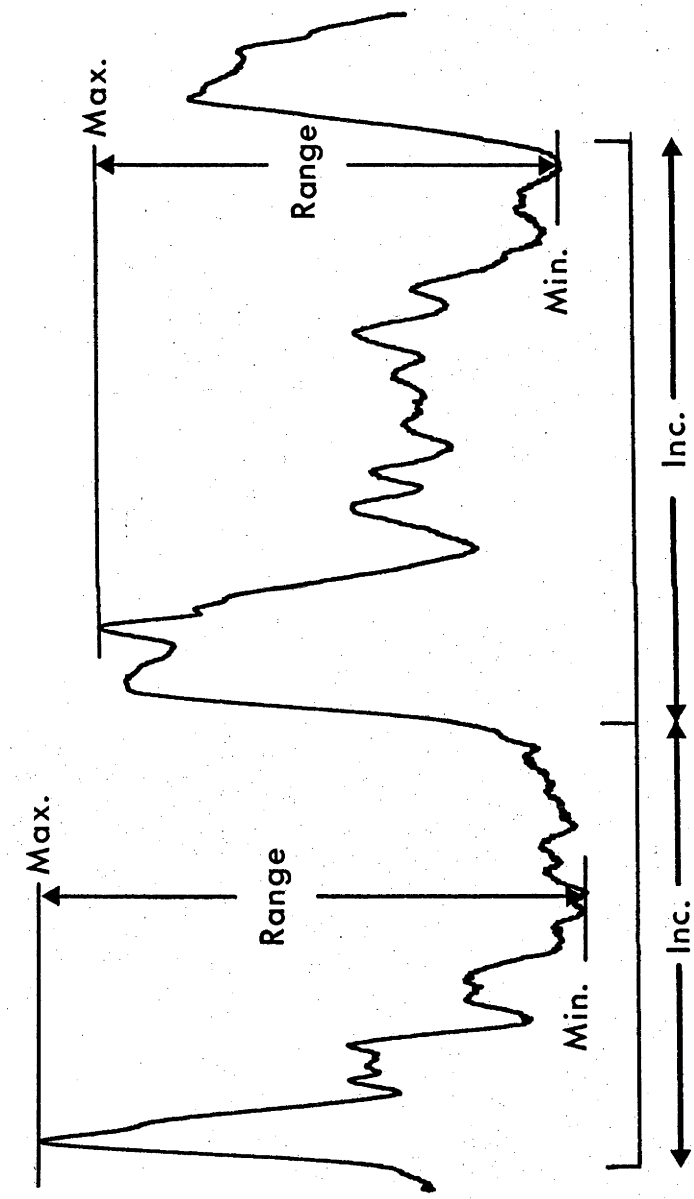


identify common increments. It will be noted that the pattern of variation in wood density is very similar in rings having the same number. This is of great assistance in demarcating the rings correctly. Of some 20,000 rings examined in this project only a few proved difficult in this respect.

Parameters of Wood Quality.

Just what parameters can most usefully be measured on the densitometric tracings is still somewhat contentious (Harris, 1969a,b). Fig. 2-4 shows a typical annual ring of P. radiata with the more readily apparent parameters identified. Maximum density is the maximum value reached in a ring and similarly minimum density is the minimum value. The difference between these two values, called here density range, is a characteristic related to veneer peeling quality, machinability and weathering properties of the wood. It has been correlated with the mechanical properties of wood (Kennedy 1968) and pulp quality (Smith and Morton, 1968). Mean density, which is calculated by dividing the area under the curve by the increment width, has been used in many studies as an overall index of wood quality. In this investigation the area under the curve was measured by dot grid counts with a dot grid having 100 dots per square inch. Maximum and minimum density were measured as the height intercepts above the baseline. All calculations were carried out by a range of computer programs developed for the I.B.M. 360/50 computer at the Australian National University (see Appendix I).

FIG. 2 - 4 Measurement of maxima,minima, and density range.



By varying the setting of the ratio arm on the microdensitometer the size of the tracing produced can be varied from 2x to 50x actual sample size. The 5x ratio arm setting was used throughout this investigation.

It is possible the values of maximum and minimum density read from the tracings may not be actual values due to machine response characteristics. To ensure that any error involved was kept constant, a constant size of scanning beam and a constant scanning speed were used at all times. It was found that a scanning beam 0.05 x 1.0mm. produced too much "fine chatter" on the density curves. For most work reported here a beam size of 0.18 x 1.0mm. was used as this gave a smooth curve but did not compromise precision.

Latewood percentage has been widely used as an index of wood quality (Edlin, 1965). Mork's (1928) rule and later modifications of it, for example by Klem and others (1945), has been used to define the earlywood/latewood boundary. The method is subjective and is suited mainly to microscopic investigations. It is also unsuited to species without marked differences in density between the earlywood and latewood zones or lacking an abrupt change in density at the boundary.

Continuous density recording methods make it possible to measure latewood percentage objectively. Phillips (1960) proposed that latewood percentage should be measured as the proportion of the ring having a density greater than a certain figure. This approach is attractive as the data are very easily read from the density tracings. There are limitations, however, since wood density varies in both the earlywood and latewood zones, especially in P. radiata (Figs. 2-3 and 2-4).

Elliott and Brook (1967) criticised the method and proposed instead that the boundary between earlywood and latewood should be the mid-point between the density values of the first-formed earlywood and the last-formed latewood. This is essentially the same definition as that put forward earlier by Green and Worrall (1964). While this definition ensures that every ring will have a latewood percentage, it bears little or no relation to the technological properties of the wood. Like the parameter "latewood ratio" (Harris, 1969b) it is descriptive in character and does not characterise wood properties in an absolute sense. The disadvantages of this approach have been discussed by Rudman (1968) and Brazier (1969), both of whom advocated division of the ring on a density basis.

In the present study latewood percentage was measured as the proportion of the ring with a density greater than 0.468. This figure corresponds with one of the wedge steps and so is marked on every density tracing. It was selected largely for convenience but lies in the transition zone from low to high density for the P. radiata used in this project.

The pattern of within ring density variation can be described better by measuring latewood percentage at several levels of density and then averaging to obtain a mean latewood percentage. As a test, mean latewood percentage over four density levels was measured in two of the fertiliser/wood density experiments. The four density levels chosen were 0.35, 0.45, 0.55 and 0.65 gm./cc. The figures were selected arbitrarily to cover the range of density normally encountered within a ring of P. radiata from the areas sampled.

Figure 2-5 shows how mean latewood percentage is measured on a number of stylised patterns of within ring density variation, and an example of its use on an actual

Mean latewood percentage is most closely related to wood density and since it describes the structure of the ring better than the other methods it is likely to be better correlated with, for example, strength properties of the wood.

Collection of such data is simple and rapid. The associated calculations are tedious but suitable computer programs can be developed to handle them.

2.4 Sample Preparation.

The field specimens used in the main part of this study were collected in two ways -

(i) from felled trees as complete discs 1 - 2 inches in thickness

(ii) from standing trees with a Solo chainsaw tree sampler (Sulc, 1967) as bark-to-pith blocks approximately one inch square in cross section.

The field specimens were dried and radial samples for analysis were cut out 3/8-inch square in cross section with a bandsaw, care being taken to ensure that the long axis was cut at right angles to the grain. In the discs the sample was cut out bark-to-bark, including the pith, and aligned across the short axis where the disc was eccentric.

All samples were extracted for eight hours in a 1:2 mixture of ethyl alcohol and benzene in a Soxhlet apparatus. In view of the age of the trees used in this study, the consequent lack of heart-wood development and the relatively low extractive content of P. radiata, this period of extraction is adequate. All density figures for P. radiata in this study are therefore extracted density.

After drying in a vacuum oven the samples were placed in a glass desiccator over a saturated solution of sodium dichromate and conditioned to 8 ± 0.05mm. percent moisture content. They were then machined to a final thickness of 6.90 ± 0.05mm. in the radial longtitudinal direction and stored in the desiccator until X-rayed. All samples used in this study were X-rayed in the radial longtitudinal direction, ie. parallel to the grain.

CHAPTER 3

SAMPLING FOR THE STUDY OF WOOD PROPERTIES

Any investigation of wood properties in a standing tree crop involves drawing conclusions from a sample which inevitably is a very small proportion of the population. Successful sampling requires a knowledge of the patterns of variation of the attributes concerned both within trees and between trees. This chapter considers the effect of within-tree variation in wood density on estimation of density of individual trees and of between-tree variation in wood density on estimation of stand average density.

3.1 Variation in Wood Density Within Trees.

General.

Within any one tree there is considerable variation in wood density. Except perhaps for the genera Thuja and Picea, the general pattern in conifers is for density to decrease from the base to the apex and to increase from pith to bark at any level, rapidly in the juvenile phase and then slowly or not at all thereafter. In very old trees there may even be a decline in density in the outer rings.

Duff and Nolan (1953) demonstrated how variation in density (or any other attribute of wood) can be represented in three "sequences". The horizontal sequence, which is the one most used for wood density studies, traces the radial change in density from pith to bark, each ring from the pith outwards being produced by cambium of increasing age. The oblique sequence traces the progression of a single growth sheath from apex to the base of the tree with the age of the cambium increasing from apex to base. The vertical sequence traces the progression of density from internode to internode down the tree at a constant ring number from the pith.

Richardson (1961) discussed the implications of this systematic pattern for sampling in studies of wood properties. He recommended that wood samples should be taken from the centre of internodes and that the samples should be located by reference to the number of internodes from the apex of the tree. If this were not possible due to the difficulty in correctly defining the age of the internodes, then sampling at fixed percentages of total tree height was advocated. For the study of the influence of environmental factors on wood properties the vertical sequence seemed to have special attraction since for any given ring number from the pith the wood was produced by cambium of the same physiological age.

The nodal specification applies particularly to the uninodal and comparatively slow growing Northern Hemisphere conifers, but sampling in a multinodal (or, more precisely, varinodal) tree such as P. radiata is not so simple. It is possible to detect the stages of growth in a young tree or the crown parts of a felled older tree (Jacobs, 1937) but it is very time-consuming. It is very difficult, on external indications, to fix the stages of growth on the lower parts of an older tree. Therefore it is not practicable to sample at a fixed number of growth intervals from the apex in any large scale investigation. It was necessary, then, to determine whether the methods of sampling commonly used for other conifers were valid for *P. radiata*.

Sampling in Juvenile Trees.

A small scale study of the within-tree variation in density in juvenile *P. radiata* was carried out prior to an extensive investigation at the Belanglo Close Spacing experiment (Chapter 5). The aim of the study was to establish the suitability of the percentile sampling approach in small trees and to determine whether a satisfactory level of precision could be obtained from density data on one radius of the sample.

The trees were seven years old when sampled and ranged from six feet to 25 feet in height. Eight trees were used from each of the fastest and slowest growing groups and were sampled at 15, 30, 45, 60 and 75 percent of tree height. No samples were taken below the 15 percent level because of the frequent presence of butt sweep in the sample trees. The variation of mean density in the 1966 sheath only was studied, as this was the only ring present at all sampling heights.

The frequent presence of compression wood is a problem in *P. radiata* in young trees or in rings close to the pith. In spite of care in alignment of the samples across the discs some anomalous high density areas were found on the tracings which after further examination were attributed to compression wood. The density tracings on opposite radii are rarely identical but the presence of compression wood, however slight, seemed to cause larger than usual differences. Consequently the density curves for 1966 from opposite radii were subjectively classified as "A" or "B" according to whether the curves appeared free of compression wood or otherwise, respectively. If there was no obvious abnormality the radius having the lower mean density was classified as the "A" curve. In this way the significance of the differences between radii could be assessed.

Variability of density maxima on the two radii was examined by a comparison of average maximum density for the three growing seasons 1964-5-6 in the two radii, classified as described above, for the 15 and 30 percent levels only.

In both the fast grown and slow grown trees the mean density decreased steadily from the base upwards (Table 3-1), the pattern of change being similar from 15 to 60 percent of tree height.

TABLE 3-1 Variation of mean density (gm./cc.) within the 1966 sheath - Belanglo trees

Group	Percentile Sampling Position				
	15	30	45	60	75
Slow Grown A	0.560	0.536	0.487	0.432	0.330
B	0.580	0.542	0.500	0.431	0.336
Mean	0.570	0.539	0.494	0.431	0.333
Fast Grown A	0.515	0.466	0.438	0.372	0.379
B	0.509	0.472	0.424	0.383	0.387
Mean	0.512	0.469	0.431	0.378	0.383

At the 75 percent level the fast grown trees showed a deviation from the previous trend, the density remaining substantially the same as that at the 60 percent level. The reason for this is that the number of growth rings at the percentile sampling points was comparable in the two groups from 15 to 60 percent, but at 75 percent there were three rings in the fast grown trees but only two in the slow grown trees (see Table 3-2).

TABLE 3-2 Average number of growth rings at each sampling height

Group	Percentile Sampling Position				
	15	30	45	60	75
Slow Grown	6.4	5.0	4.0	3.0	2.0
Fast Grown	6.2	5.0	4.5	3.5	3.0

Consequently the 1966 ring at the 75 percent level was physiologically older in the fast grown trees and therefore of higher density.

There were only small, and statistically non-significant differences between density values on the "A" and "B" curves indicating that in trees of this age and size sufficiently precise results could be obtained from data from one radius only.

The weighted average density of the entire 1966 ring (up to the 75 percent level) was calculated and compared with values of mean ring density at several sampling positions in the stem. The average density data on the two radii for each tree at each level were used to construct a curve of variation in mean density with height for each tree. From these curves values for mean density were read off at 1 foot, 2 feet and 4.25 feet above ground. Average values for each group are presented in Table 3-3.

TABLE 3-3 Comparison of efficiency of sampling methods in small trees.

Group	Sheath Density (a)	Density(gm./cc.) at Sample Position			
		15%	1 Foot	2 Feet	4.25 Feet
Fast Grown	0.442	0.512	0.541	0.528	0.497
Slow Grown	0.506	0.570	0.576	0.551	0.460
Diff. as % of slow grown	-12.6	-10.2	-6.1	-4.2	+7.2
Correlation Coefficients (all trees)(b)		0.853***	0.794***	0.738***	0.482 NS

Note: (a) Weighted average sheath density in gm./cc.

(b) Correlation between whole sheath average density and density at the various sampling positions, for all 16 trees combined.

Sampling at breast height (4.25 feet) indicated the fast grown trees had the higher wood density, whereas the reverse was true taking the 1966 sheath as a whole. Sampling at 15 percent of tree height, 1 foot and 2 feet above the ground all consistently overestimated whole sheath density. The 1-foot and 2-feet sample data, while being highly correlated with whole sheath density, underestimated the differences between the fast and slow grown trees to a far greater extent than did the 15 percent data, and for this reason the latter is the most suitable sample. It is reasonable to assume the same relationship would hold for whole radius and whole tree data. Variation in the number of growth rings at the higher levels (Table 3-2) indicated that sampling at higher than 30 percent of tree height would have been less efficient. There are also practical disadvantages in working with smaller samples.

There was no significant difference between estimates of maximum ring density on the "A" and "B" radii. Compared with the mean maximum for both radii, the "A" figure under and overestimated maximum density by about two percent for the fast and slow grown trees respectively (Table 3-4). Therefore when the data were averaged over a number of rings (three in this case) satisfactory results were again obtained from one radius only.

TABLE 3-4 Variation in maximum density on opposite radii average maximum (gm./cc.) for 1964-66

Group	Radius (a)		Mean
	A	B	
Slow Grown (b)	0.667	0.644	0.656
Fast Grown (c)	0.686	0.717	0.702
Mean	0.677	0.681	0.679

Note: (a) A and B as defined in text
(b) Based on six samples at 15 percent and six at 30 percent height
(c) Based on seven samples at 15 percent and seven at 30 percent height.

Sampling in Large Trees.

In this discussion, large trees will be taken to mean those of merchantable size, that is, above about 40 feet in height.

In many studies involving large trees the sampling point has been breast height. A relationship has been established many times between density in a breast height sample and whole tree density (eg. Zobel, Henson and Webb, 1960). This relationship has been assumed to apply over a range of sites, but, as discussed in a later chapter, this may not always be a justifiable assumption.

Sampling at breast height is justified where there are no large differences in development between trees and there are no important differences in tree age. The errors associated with sampling at slightly different relative positions in the trees are then small compared with the differences between trees. The practical aspect must also be considered. Where sampling has to be non-destructive it is impractical to remove samples from points more than five feet above ground in any large scale investigation.

The suitability of the breast height sampling point in large trees of <u>P. radiata</u> is illustrated by Table 3-5. The data came from nine sample trees aged 13 years, all codominants from within a few yards of each other in the same stand.

TABLE 3-5 Comparison of efficiency of sampling positions in large trees.

Sampling Position	Correlation Coefficient (a)	Regression S.E. of Est.
Butt sample, weighted, whole radius	0.812**	0.016
10% of tree height, weighted whole radius	0.814**	0.014
20% of tree height, weighted whole radius	0.900***	0.010
Breast height, weighted whole radius	0.878***	0.012
Breast height, unweighted average of both radii	0.907***	0.010
Breast height, unweighted lower density radius	0.712*	0.017
Breast height, unweighted higher density radius	0.865**	0.012

Note: (a) relationship with weighted density of the whole tree to a three-inch merchantable limit, calculated on the program DENDRY (Appendix I).

There was no significant improvement in the relationship when percentile sampling was used and there also seemed to be no advantage from weighting the breast height sample. The butt sample was the least suitable sampling level of those tested. The correlation coefficients for the individual radii at breast height indicated that two samples per tree at 180^{o} to each other were to be preferred to one sample only. Consequently, two samples per tree were used in this study, except where non-destructive sampling was necessary, when only one sample per tree was used.

The breast height-whole tree correlations are comparable with those obtained for P. radiata in New Zealand by Harris (1965), using whole disc samples and trees aged from 25 to 43 years.

3.2 Variation in Wood Density Between Trees.

In an even aged stand of conifers there is wide variation in wood density from tree to tree, but the reasons for this variation have never been satisfactorily explained. Many investigators have attempted to establish the influence of such factors as growth rate, crown class and crown size (see Spurr and Hsuing, 1954) and proportion of clear bole (Zobel, 1956). Zobel and Rhodes (1955) concluded that all these other factors accounted for little of the variation between trees, and that the genetic factor must be of importance. The more recent studies in clonal plantations of P. radiata by Fielding and Brown (1960) supported this opinion. Clones differed widely in the density of their wood, but within a clone there were relatively small differences between trees.

The large differences in density between trees in a seedling plantation noted by Fielding and Brown (loc. cit.) were also evident in the present study. Table 3-6 lists the weighted whole tree density values for nine trees aged 13 years, all codominants and all growing within a few yards of one another.

TABLE 3-6 Variation in whole tree density between trees aged 13 years.

Tree No.	Weighted Whole Tree Density gm./cc. (to 3" merch.limit)	Variance in Density Within Trees (a)
1	0.413	0.000856
2	0.403	0.001054
3	0.427	0.001591
10	0.386	0.000470
11	0.434	0.001266
12	0.418	0.001704
16	0.429	0.001761
17	0.380	0.000615
18	0.452	0.002140
Variance Between Trees 0.000535		

Note: (a) Variance in weighted average density at each 10 percent of tree height from butt to 80 percent.

Trees for sampling might be selected on a completely random basis but efficiency of sampling would be greatly increased by some form of systematic or stratified random selection if wood density were correlated with some easily assessed external feature of the tree. For this reason the association of wood density with a number of morphological characteristics was investigated in four groups of trees on four sites of differing productivity. All groups came from the same soil type in the same plantation and the trees in each group covered the whole range of size classes. All trees were aged 14 years.

Linear regressions were calculated to relate weighted whole tree density to each of the following characteristics :

X_1 - Tree height (ft.).

X_2 - Height to base of green crown (first complete green whorl).

X_3 - Crown width (maximum width).

X_4 - Tree volume (cu. ft. U.B. to a three-inch top).

X_5 - Diameter at breast height (U.B.).

X_6 - Crown class (dominant = 1, codominant = 2, subdominant = 3, suppressed = 4).

X_7 - Stem taper (see text below).

X_8 - Length of green crown ($X_1 - X_2$).

X_9 - Crown volume index ($X_3 \times X_3 \times X_8$).

X_{10} - Height / D.B.H. (ft./in.).

Variable X_7, stem taper, was the regression coefficient of the regression of cross-sectional area on height in the tree for percentile heights from 10 to 70 percent. If the butt swell portion of the bole is excluded there is a very good linear relationship between these two parameters up to at least 70 percent of tree height (Gray, 1944). X_9 was not actual crown volume but a variable assumed to be closely related to it.

When the data for all plots were pooled there was a strong association of low wood density with the larger trees, a high degree of stem taper and the higher crown classes. Height to the base of the green crown did not appear to bear any relationship to wood density. Density was, however, negatively correlated with the other crown parameters of width, length and crown volume index (Table 3-7, last column).

Since the size and distribution of the living crown are the principal intrinsic factors governing the patterns of growth and cell characteristics, and therefore wood density (Larson, 1962), these correlations with crown attributes are to be expected. That the correlations are not high is due to their being very crude measures of crown size. The high correlations of density with diameter, volume, tree height and crown class are not due to the influence of these characteristics *per se* but basically to the attributes of the crown. High values of all of them are associated with a large crown surface and, to some extent, variation between trees in photosynthetic efficiency. However, the significance of the latter in large trees is not known as yet.

TABLE 3-7 Correlation coefficients between whole tree density and several morphological characteristics.

Tree age 14 years.

Variable	Plot Site Index (a)				All plots combined (d)
	50-55 (b)	45-50 (b)	40-45 (c)	35-40 (c)	
X_1 Height	-0.680*	-0.419	-0.591	-0.222	-0.469**
X_2 Crown ht.	0.189	-0.056	0.185	0.062	-0.088
X_3 Crown width	-0.525	-0.247	-0.319	-0.310	-0.348*
X_4 Tree vol.	-0.844**	-0.581	-0.569	-0.310	-0.576***
X_5 D.B.H.	-0.898***	-0.538	-0.600	-0.417	-0.613***
X_6 Crown class	0.700*	0.538	0.598	0.153	0.481**
X_7 Stem taper	-0.912**	-0.614	-0.623	-0.587	-0.635***
X_8 Crown length	-0.611	-0.248	-0.653	-0.246	-0.433**
X_9 Crown vol.	-0.510	-0.395	-0.431	-0.185	-0.346*
X_{10} Ht./DBH	0.920**	0.393	0.517	0.606	0.560***

Notes: (a) Site index at age 10 years

(b) $n = 10$ $r_{.05} = 0.632$, $r_{.01} = 0.765$, $r_{.001} = 0.872$

(c) $n = 9$ $r_{.05} = 0.666$, $r_{.01} = 0.798$, $r_{.001} = 0.898$

(d) $n = 38$ $r_{.05} = 0.325$, $r_{.01} = 0.418$, $r_{.001} = 0.519$

The high correlation of wood density with variable X_{10}, the ratio tree height/diameter at breast height, is somewhat unexpected. Possibly the ratio integrates, to some extent, the influence of crown attributes on several other parameters since it is related to taper and tree volume.

The association of low wood density with high stem taper is in agreement with the work of Trendelenberg (1932, 1935), Volkert (1941), and Turnbull (1942), who have shown that a tree may meet its requirements for stem strength by production of a small volume of high density wood or a large volume of low density wood, with consequent differences in stem taper.

A statistically significant association between stem taper and wood density has not previously been demonstrated for P. radiata. Fielding and Brown (1960) were unable to find a significant relationship between wood density at breast height and form factor (the ratio of underbark tree volume to the volume of a cylinder of the same height and diameter breast height of the tree), although their data does show a similar trend to that found in the present study.

The marked difference between sites in the strength of the correlations presented in Table 3-7 has a practical aspect. The data indicate that environmental factors have a greater influence on wood density on higher quality sites. The mechanism for such a relationship is through the effect of site quality on crown attributes. On the better sites the attributes of the crown are largely the result of competition between the trees, but on the poorer sites crown attributes are determined by the limitations of the site itself. That competition between trees was not the dominant factor on poor sites at Flynn Creek is shown by the incidence of competing ground vegetation. On the best of the four plots there was none, on the 45-50 plot there was a moderate amount, and on the two poorest plots it was quite dense.

The point deserves further study over a wider range of site quality and stand age, but if so, then there is scope for modifying wood density by simple silvicultural measures on good sites but not on poor sites.

The strong negative correlation of wood density with diameter, tree volume and taper means that any of these could be used to stratify the stand for sampling. Since diameter is the most easily assessed characteristic it is the logical one to use in practice.

3.3 Variation in Wood Density Between Stands.

The development of adequate sampling methods for the estimation of average wood density of a standing tree crop has received surprisingly little attention. Most studies which set out to show differences in wood properties between stands confine sampling to dominants and codominant stems only. Furthermore the selection of the sample trees is usually subjective, thus introducing an unknown element of bias. "Valid sampling is achieved when the distribution of values in the sample represents in some way the distribution of the values in the population" (Pearson, 1952).

The literature on sampling for the estimation of wood properties refers in the main to the derivation of species means, often from sawn timber samples (Hellawell and Warren, 1956, Harris and Hellawell, 1958, Nair and Mukerji, 1957, Pearson and Williams, 1958). The general conclusion of all these studies was that best results are obtained from fewer samples per tree from a larger number of trees than vice versa.

Krahmer and Snodgrass (1967) developed a sampling plan for determining wood properties at several levels of precision in natural, uneven aged stands of western hemlock. Sample trees were located randomly within diameter classes, the number in each class being related to the proportion by volume in each class. For wood density as few as 10 trees were required to estimate locality averages within ± 5 percent of the true mean for one locality, but twice as many were required for another locality, for the same level of precision. Using two random samples per tree resulted in fewer trees being necessary for the same precision of estimate.

Harris (1967) described a study of two methods of estimation of stand average wood density. "Point samples" were increment cores from groups of 25 trees from the four corners of 100-acre compartments while "line transect samples" were cores from 25 trees taken at fixed intervals along lines running diagonally across the compartments. Either method would enable average wood density within a uniform stand to be estimated to within ± 1 lb/cu. ft. (0.016 gm./cc.) at the 95 percent probability level. A uniform stand of more than a few acres in extent is comparatively rare in P. radiata so the "line transect" approach has less potential than the "point samples" method.

Wolski (1965, 1968) compared several approaches to sampling and recommended that selection of sample trees be based on their diameter. The number of trees from each diameter class should be proportional to the number of trees in a class and the total number of samples should be calculated for each situation and depend on the degree of precision required. Wolski did not, however, comment on the method of selection of the sample trees, that is, whether or not it should be subjective.

While a completely random selection of trees is the theoretical ideal, it is seldom practicable in forestry. Some form of stratification or a systematic method is usually adopted. If the selection of individual trees were random, then Wolski's method is essentially a stratified random one and has much to commend it. In practice it would require marking out a plot on the ground, enumerating the stems and then applying some random selection process within specified diameter classes. Such a procedure would be very time consuming, so an alternative was sought which was both statistically sound and more rapid in application.

Before considering sampling methods further an estimate of the number of trees required was necessary. Sample size can be calculated using the formula

$$n = \frac{t^2 \ s^2}{D^2}$$

where t is the appropriate value of Student's "t",
s^2 is the estimate of population variance,
D is the required precision of estimate of population mean in gm./cc.

Breast height density data from the Flynn Creek KCl experiment (Chapter 6) were available for a preliminary estimate of the population variance. Although the distribution of tree sizes was not fully representative of the population and the density data applied to the outer six rings only, the stand was of a similar age and condition to those for which further sampling was planned. The pooled variance for all 72 trees from the experiment was 0.002808 and the value of D selected was 0.030. Since this variance was assumed to be the population variance it was appropriate to use "t" values for infinity. These values were inserted into the above equation giving an estimated number of sample trees of 12 for the 95 percent level of probability and 21 for the 99 percent level. For lower values of D these figures are correspondingly higher. Thus, it seemed likely that at least 20 sample trees per plot would be required to achieve a satisfactory precision of estimate, and while this was not an excessive number of trees, it would clearly be an advantage if the number could be reduced.

The ranked-set sample method offered a possible way of combining these two requirements of minimum possible sample size and ease of application in the field. The theory of the method is outlined by McIntyre (1952). It was developed initially for sampling of pasture or arable crop yields and the only other published reference to the technique (Halls and Dell, 1966) also used it to estimate forage yields.

Briefly, the procedure is as follows: within a set of _n_ random items, take the largest with respect to the characteristic being sampled in the first set, the second largest in the second set, and so on to the smallest in the _nth_ set.

The special features of ranked-set sampling are

(i) the _n_ items are an unbiased sample of the population

(ii) where there are no errors in ranking and the frequency distribution of the characteristic being measured is symmetrical, the efficiency of estimation of the mean, relative to random sampling, is about $\left(\frac{n+1}{2}\right)$, that is, for sets of 5, $\frac{5+1}{2}$ or 300 percent. In other words, 5 ranked-set samples are as efficient as 15 randomly selected samples.

(iii) It is particularly suited to the situation where the local variation (such as density between trees) is greater than the variation between set areas (average density from one part of a stand to another).

The precision of the method depends on the accuracy with which ranking is carried out and unfortunately trees cannot be ranked visually for their wood density. However, density is strongly negatively correlated with the attributes of vigour, so it was decided to test the technique ranking the trees on their most easily assessed parameter - diameter at breast height. This procedure is very similar to that advocated by Wolski, since for a set of reasonable size, say 10, the frequency distribution of diameters in the set will approximate that of the stand, but the selection of sample trees is completely objective.

Trial of Ranked-Set Sampling.

For a trial of the technique a set size of 10 trees was selected as a compromise between an adequate sample of the range of diameters in a stand, speed of ranking the trees and likely necessary sample size. A level of precision of estimate of $\pm$ 0.020 gm./cc. at the 99 percent half confidence limit was chosen.

In the discussion which follows the individual groups of 10 trees, from each of which one sample tree was drawn, are referred to as sets. The clusters of sets are called plots, although they are not plots in the usual sense of the term.

Four plots were sampled in a 14-year old stand of *P. radiata* at Flynn Creek Tree Farm. They were spread over a range of site quality classes as previous work had indicated that the correlation between wood density and tree diameter was poorer on low quality sites and it was desired to fix a sample size to cover all conditions.

Each ranked-set plot was located adjacent to a permanent inventory plot to ensure that all were, in fact, on sites of different quality. In selecting the sample tree in each set a tree was first nominated as the "base" tree. For the first of the sets the sample tree was the largest tree of the 10 closest to the "base" tree. The next set was located as close as possible to the first, but so as to not include any trees which had been considered in the first set, and so on. Unless there was no possible doubt about the ranking in a set, the diameters of the trees were measured.

The trees were felled and discs removed at breast height. Mean density was measured for each ring from the pith to the 1967 ring on two opposite radii (see Chapter 2). From these individual ring data weighted average "disc" density was calculated, weighting each ring by its cross-sectional area.

The variance applicable to the mean of the 10 trees in each plot is given by:

$$\frac{[S_1^2 + S_2^2 + S_3^2 \; \ldots\ldots\ldots \; S_{10}^2] \times 0.1}{10}$$

where S_1^2 is the variance of the four first-ranked trees,

S_2^2 is the variance of the four second-ranked trees, and so on.

The average variance of the ranks for the four plots was 0.001456, thus the variance to attach to the plot average density was 0.000146. This figure was used with the sample size formula previously given, to estimate the optimum number of sample trees required to three levels of precision, at both the 95 and 99 percent half confidence interval.

TABLE 3-8 Estimated sample size for ranked sets (a)

Percent Half Confidence Interval	Precision of Estimate (gm./cc.)(b)		
	0.030	0.020	0.010
95	1	2	7
99	2	4	15

Note: (a) To nearest whole number.
(b) "t" value for nine degrees of freedom used.

On these data plot average wood density was therefore estimated with a precision of $\pm$ 0.010 gm./cc. at better than the 95 percent level of probability.

For the purposes for which it was planned to use ranked-set sampling in this investigation it was decided to continue using a set size of 10. It can be seen from Table 3-8 that a set of four was sufficient, in the first four plots, to give the required precision of 0.020 at the 99 percent half confidence interval. However there was the possibility that further sampling might indicate that a higher estimate of variance should have been used, so a set of 10 would give a large safety factor.

The additional data available from the site quality - wood density study (Chapter 4) enabled a more precise determination of the required sample size. The weighted data from 16 plots were pooled and the variance applicable to the plot means calculated by the procedure outlined earlier.

The variance estimate for 16 site quality plots was virtually identical with the original estimate - 0.000145 compared with 0.000146. Therefore, if weighted average density at breast height were the only parameter under study, a set size of four would be adequate at Flynn Creek Tree Farm to predict average stand wood density $\pm$ 0.020 gm./cc. at the 99 percent half confidence limit.

If, however, it is desired to compare wood density at the individual ring level, then a larger set size is necessary, since density is always more variable between individual rings than between weighted "disc" averages. Limited testing did indicate, however, that the set size of 10 was sufficient to maintain the levels of precision chosen for the present study.

For optimum efficiency the set size should be checked for each area to be sampled. There was evidence that the required number of sample trees was different on the two main soil types at Flynn Creek. A difference in the required sample size between two localities was also noted by Krahmer and Snodgrass (1967) for western hemlock.

Even with a set as large as 10, ranked-set sampling is extremely rapid and easy to use in practice. Selection of the sample trees in a 10-tree plot usually required no more than 30 or 40 minutes.

A 10-tree plot probably offers little advantage over random sampling in terms of sample size, but any reduction in sample size is worthwhile when the difficulty of procuring and processing wood samples is considered.

In conclusion, the ranked-set technique is well suited to sampling of wood properties in standing trees. Its simplicity is equivalent to the subjective selection methods usually employed but its inherent absence of bias is a great improvement over those methods. The technique may have further application in forestry and deserves further study.

CHAPTER 4

SITE QUALITY AND WOOD DENSITY

4.1 Introduction and Review of the Literature.

The influence of site on the wood properties of trees has been a subject of interest for many years. In spite of a long period of study, however, there is still little agreement as to the influence of site on wood density. A number of investigations have dealt with stands covering a wide geographic range, thus introducing a separate source of variation to the data, namely that due to climate. In the present study, site, or more specifically site quality, is taken to mean the productive capacity of an area within any one geographic or climatic zone. In the review which follows, only those studies concerned with variation in wood density with site as here defined will be considered.

Since a comprehensive review of earlier work was published by Spurr and Hsuing (1954), only work more recent than this will be covered here. Spurr and Hsuing concluded that while major differences in site quality do influence wood density, the correlation between the two factors is not high, and the relationship frequently cannot be found even under carefully controlled experimental conditions.

Larson (1957) found that site quality had no effect on the wood density of slash pine (P. elliottii Engelm).

However he did find that density increased with increasing "moisture equivalent values" and increasing silt and clay content of the B horizon, which are usually associated with better quality sites.

A significant negative association of wood density with site index over the range 90 to 160 for western hemlock (Tsuga heterophylla Sarg.) was reported by Wellwood (1960). This association was found only in the lower bole and not in the mid or upper bole.

Schniewind (1961) concluded there was no overall difference in wood density for Californian red fir (Abies magnifica A. Murr.) on three different sites. However, trees on the poorest site studied had a relatively even density from pith to bark whereas on the two better sites there was a more marked gradient in density from pith to bark.

Zobel and Rhodes (1955) could detect no effect of site index within the range 80-120 for loblolly pine (P. taeda L.) although Zobel later (1956) found a weak negative relationship between wood density and site index for loblolly pine in East Texas.

All these studies and many of those reported by Spurr and Hsuing were concerned with natural stands where the existence of different genetic populations might have influenced the results (Zobel, 1956). Furthermore these workers have used stands in which there was some variation in tree age. For example, Wellwood used 39 trees ranging in age from 56 to 78 years. Much more precise results might be expected from studies in planted stands where both these complicating factors are eliminated.

Jayne (1958), working with 35-year old planted red pine (P. resinosa Ait.), reported lower wood density on the better of two sites and a changed relationship between density and height in the tree. The slope of the relationship tended to increase from the poorer to the better site. Later, Hannah (1969) confirmed that red pine on poorer sites produced wood of higher density.

According to Sunley and Lavers (1961) wood density of Sitka spruce (Picea sitchensis Carr.) grown in the U.K. differed significantly between sites within regions.

On the basis of a study of wood properties of branchwood of seven-year old clonal material Hamilton and Harris (1965) concluded that slightly less dense wood was produced on the better of two sites by loblolly pine but this was not so for slash pine. However since these workers failed to establish a close relationship between branch and bole wood density, the validity of their conclusions is open to some doubt.

More recently Nicholls (1967) has shown a highly significant difference in the density of the wood of P. pinaster Ait. grown on two sites in Western Australia. He attributed the differences to variation between the two sites in water availability during the latewood phase of growth.

There have been comparatively few attempts to relate wood density of P. radiata to site quality. Langlands (1938) noted only slight and inconsistent differences in density of timber from four plantations of the species in South Australia. In their extensive study of the variation of wood density in P. radiata in the Australian Capital Territory, Fielding and Brown (1960) concluded that site differences had little influence on the average density of wood within particular localities and the effect of site on density was not consistent. Significant differences between sites were found in three samplings: in two of these the lower site quality was associated with significantly higher density and in the other it was associated with a significantly lower density. In an unpublished study by Morales (1968) site index had a highly significant negative association with wood density of P. radiata grown in Chile, although it is possible this effect was partly due to variation in climate and soil type.

The situation in respect of the influence of site quality on wood density of P. radiata is, then, inconclusive and further investigation is desirable.

Göhre (1958) was of the opinion that within site variation in wood density was greater than the variation between sites and suggested that much of the contradiction in the literature was due to differences in sampling techniques and the interpretation of results. Certainly much of the published work has been based on very few sample trees and the validity of the sampling approach is frequently questionable. Furthermore in many accounts the description of the study area is so inadequate that one is unable to judge whether the reported effects are truly due to site quality and not to some other factor such as climate or soil type.

Almost all of the reported work has been undertaken using breast height samples only, making the assumption that the same breast height - whole tree density relationship is applicable to widely differing sites and to trees of differing ages. Under some circumstances, however, the same relationship might not apply.

Stern (1963) found "the mean curve of density with height in the tree was normally well described by a second degree polynominal". There was significant differences in mean curves between stands, but not between the different classes of diameter, form and dominance of trees from the samd stand.

Jayne, as mentioned earlier, found a lower rate of change of density with height in the tree on the better of two sites and the data of Wellwood (1960) indicate a similar trend.

Even within the one stand there can be differences in the variation of wood density with height. Baker and Schottafer (1968), working with 25-year old red pine, showed density increased with increasing height in the tree in the shortest trees but in the intermediate and tallest trees it decreased with height in the lower bole and increased at higher levels.

For a species such as P. radiata with a rapid growth rate and rapid response to environmental conditions it is possible there are significant differences in the density-height in tree relationship between sites with consequent effects on the validity of results based on breast height data. The present investigation of the influence of site quality on wood density therefore had two aims:

(a) to show whether there were between site differences in the distribution of density in the tree, and

(b) to show whether there were real differences in wood density over a range of site quality.

The Flynn Creek Tree Farm of A.P.M. Forests Pty. Ltd. near Traralgon in Central Gippsland, Victoria, was chosen as the study area.

The Study Area.

The Flynn Creek Tree Farm is located about 10 miles south east of Traralgon, Victoria (Fig. 4-1). The climate for the region is temperate sub-humid. Distribution of rainfall throughout the year is fairly even, averaging 29 inches per year at the study area. The Tree Farm is about 12,000 acres in extent and is situated partly on deep sands over gravel and partly on shallow silty loams over clay on rolling topography at 200 to 400 feet above sea level.

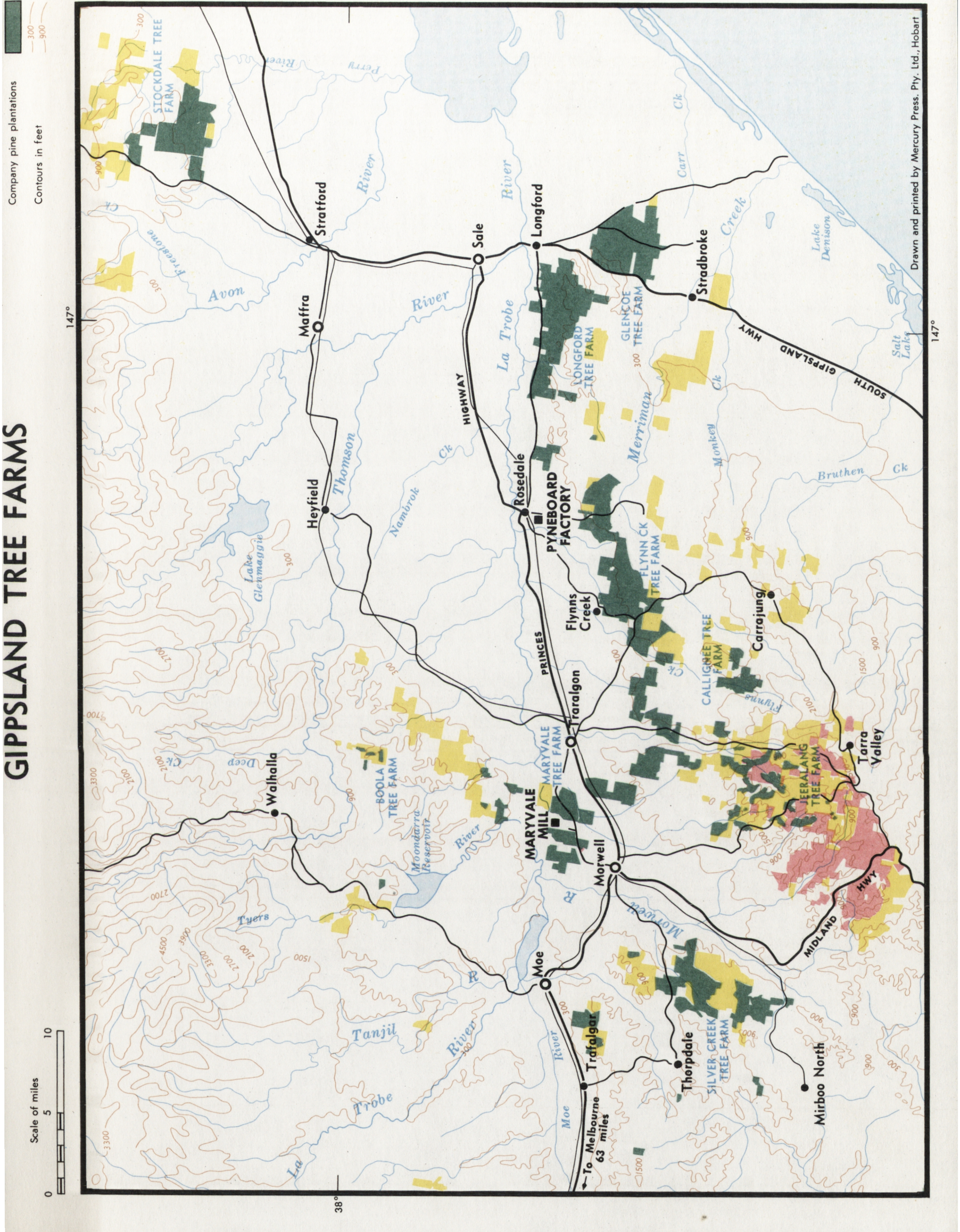
Most of the plantation area was used for sheep and cattle grazing for about 40 years prior to conversion to pines. The first plantings were in 1953 and have averaged about 1000 acres per year until 1966. All the Tree Farm has been established by planting with seedlings of quite random genetic constitution.

Tree growth is very variable over the area, not being correlated with simple factors such as soil texture and depth (Kloeden, 1969). For management purposes the area has been mapped and stratified into productivity classes based on predominant height at age 10 years (Dargavel, 1969). The strata are designated by height intervals such as 35-40, 40-45, etc. Most of the Tree Farm is in the classes 40-45 and 45-50, with smaller areas of 35-40 and 50-55.

The Sampling Plan.

Stands of the one age class only, the 1954 planting, were sampled in March 1969. A preliminary study (Chapter 3) had indicated that a ranked-set sample of 10 trees was a suitable sampling unit. A sampling plan was proposed to

FIG. 4-1   The Flynn Creek study area.



include the four site index classes at three separate localities in the plantation (two on one soil type and one on the other), with two replicate sampling units (referred to hereafter as the plots) - a total of 24 plots. However, widespread severe wind damage in November, 1968, entirely eliminated one of the localities from consideration as well as the only area of the 50-55 class in one of the remaining localities.

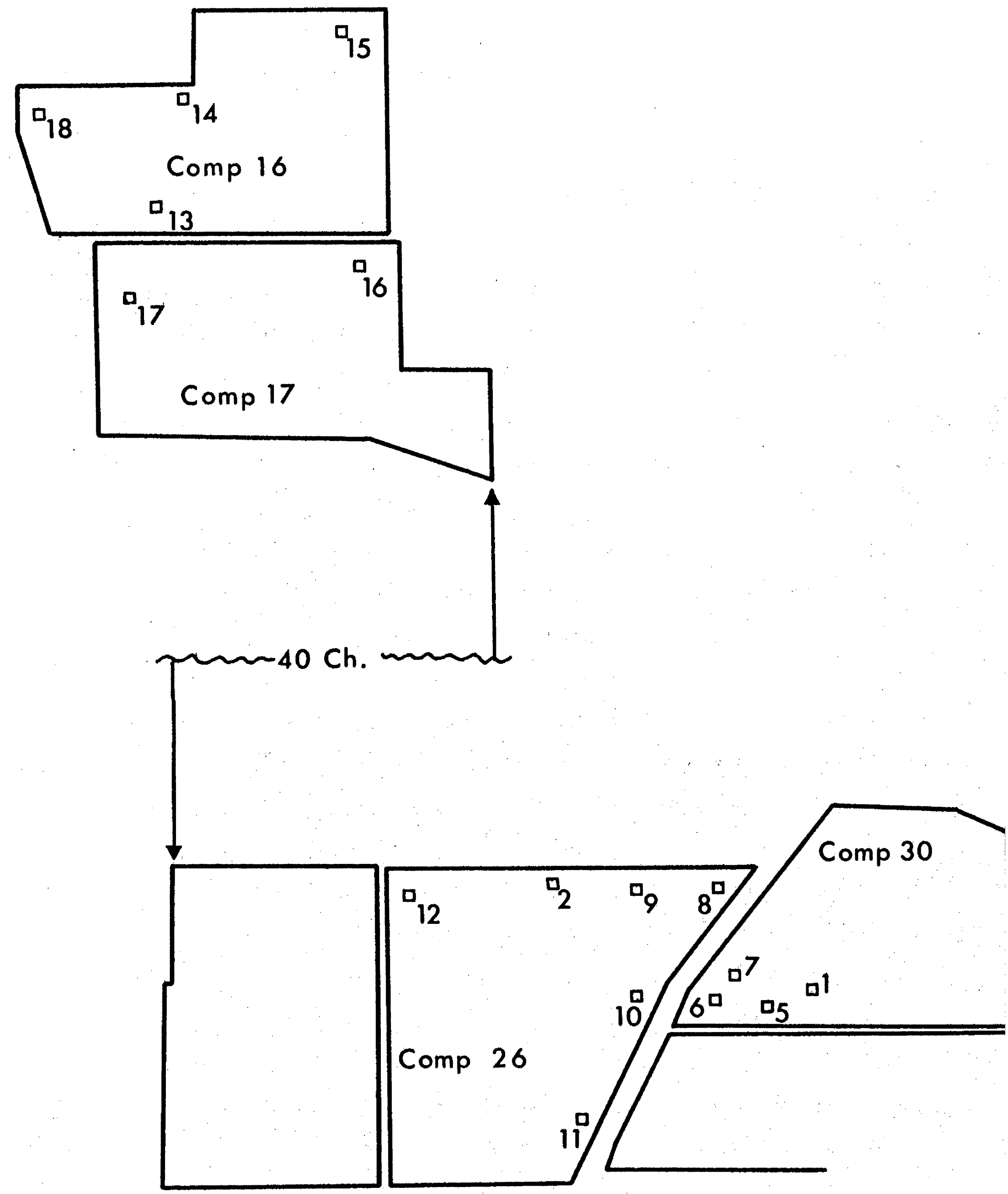
The revised sampling plan was, therefore, two localities (one on each soil type), three site index classes (35-40 up to 45-50), with two replicates - a total of 12 plots. In addition, four plots were located in the only remaining area of the 50-55 site class to obtain an estimate of the within-stratum variance. Location of the plots is shown in Fig. 4-2. Breast height samples were removed from each tree and processed as outlined in Chapter 2.

One plot in each of the four site index strata was used to study the changes in wood density with height in the tree. These will be referred to as the within-tree plots. As well as the breast height sample, discs were removed from each tree at the butt and then every 10 percent of tree height up to 80 percent. These plots were all on the sand soil type.

All ranked-set plots were situated as close as possible to a permanent inventory plot, or the location of a temporary plot used during the initial site index stratification. This procedure ensured that each plot was located in the correct stratum.

Mean ring density data for corresponding rings on opposite radii of each sample were averaged and then used to compute weighted average density, weighting by the sectional area of each ring. Maximum and minimum density were measured on each ring from pith to bark and similarly averaged on opposite radii.

FIG. 4-2 Location of ranked-set plots, Flynn Creek Tree Farm.



4.2 Results and Discussion : The Within-Tree Study.

Site Quality-Density Relationships at Points Other Than Breast Height.

The data from the four within-tree plots were analysed to determine whether there were differences in weighted average density between sites at percentile heights up to 50 percent. Data for heights above 50 percent were not used in the analysis as samples did not extend above that level in two of the smallest trees in the 35-40 plot. A randomised block analysis of variance was used, with the tree ranks as blocks. That is, block one comprised the first-ranked tree in each plot, block two the second-ranked trees, and so on.

Only in the butt samples was there a large difference between plots (sites). Butt density in the 50-55 and 45-50 plots was significantly lower (at the one percent level) than in the 40-45 plot. From 10 percent to 40 percent height there were no significant differences between plots, but at 50 percent density in the 35-40 plot was significantly lower (at the five percent level) than in the 40-45 plot (Table 4-1).

TABLE 4-1 Variation in wood density with height in tree on four site qualities

Percent Height in Tree	Plot Means(gm./cc.) (a)				LSD	
	S.I. 50-55	S.I. 45-50	S.I. 40-45	S.I. 35-40	P=.05	P=.01
0 (butt)	0.505	0.512	0.554	0.531	0.030	0.041
10	0.462	0.469	0.487	0.471	0.034	0.046
20	0.452	0.447	0.457	0.455	0.029	0.039
30	0.439	0.437	0.439	0.432	0.020	0.027
40	0.439	0.426	0.433	0.419	0.026	0.035
50	0.422	0.416	0.427	0.404	0.023	0.032
60	0.414	0.402	0.399	0.399	-	-
70	0.402	0.388	0.391	0.381	-	-
80	0.387	0.371	0.383	0.388	-	-

Note: (a) Each figure the mean for 10 trees for the levels 0 to 50 percent. Above 50 percent means are based on progressively fewer trees.

These data may be summarised as follows: in the lower bole wood density tended to be higher in the poorer site classes, at about 20 to 30 percent of tree height there was little difference between density in the four sites, and above 30 percent of tree height there was a tendency for wood density to be higher on the better site classes.

The Breast Height-Whole Tree Density Relationship.

If the variation in the trend of density with height in tree between sites were sufficiently large it would necessitate a different relationship of breast height density to whole tree density for each site. To examine this possibility the regressions were computed for the 10 trees in each plot and are given below:-

50-55, $Y = 0.040 + 0.875D$,

45-50, $Y = 0.163 + 0.611D$,

40-45, $Y = 0.125 + 0.706D$,

35-40, $Y = 0.145 + 0.661D$,

where Y is weighted whole tree density to a three-inch top and D is the weighted average density at breast height. There is no significant difference between the four equations, therefore they were combined to give a preliminary breast height-whole tree equation, applicable to trees 14 years of age growing on the sand soil type at Flynn Creek Tree Farm. The equation is $Y = 0.117 + 0.715D$, with a standard error of estimate of 0.018 gm./cc. and a coefficient of determination of 0.611.

The results of this study indicate that, for trees of this age at least, an investigation of the variation in wood density with site quality can validly be based on breast height data alone.

4.3 Results and Discussion : The Main Study.

Site Index and Wood Density.

There was no significant difference in weighted average density at breast height over the range of site index from 35-40 to 45-50. Data for the 12 plots used in the main study are given in Table 4-2.

TABLE 4-2 Weighted average density - site index study plots. Based on 120 trees.

Site Index	Sand Type		Shallow Silty Loam	
	Rep. 1	Rep. 2	Rep. 1	Rep. 2
45-50	0.481(a)	0.457	0.445	0.422
40-45	0.498	0.473	0.442	0.431
35-40	0.493	0.510	0.440	0.439

Note: (a) Each figure is the mean of 10 trees in a ranked-set plot.

On the sand soil type there was a trend for wood density to be higher on the poorer sites, but there was no such trend on the shallow silty loams. Inspection of Table 4-2 will reveal a consistent difference in wood density between the two soil types. Analysis of variance confirmed that the difference is a real one (Table 4-3).

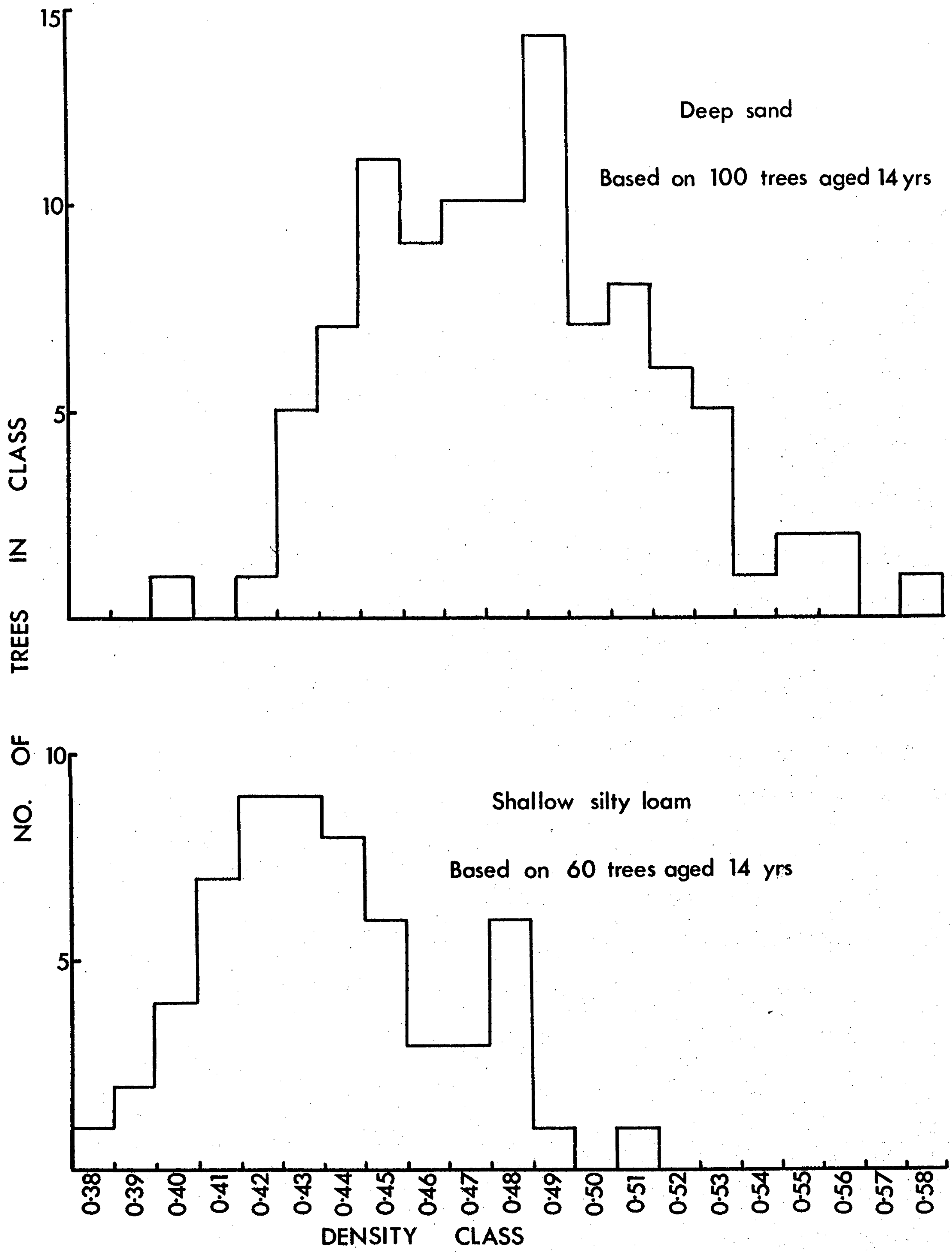
TABLE 4-3 Analysis of variance site-density data

Source	D.F.	Mean Squares	F - ratio
Soil Type	1	0.007154	19.81**
Site Index	2	0.000370	1.03 NS
Soil Type x Site	2	0.000175	< 1 NS
Error	6	0.000361	

The difference between wood density in trees from the two soils is further demonstrated by their frequency distributions of density at breast height (Fig. 4-3). Data for the histogram for the sands are drawn from the six plots from Table 4-2 plus the four plots in the 50-55 site class, whereas histogram data for the silty loams are from the six plots in Table 4-2 only.

The history of the two localities was examined to check if any differences in past treatment might explain these results. The only real difference between the two localities was in fertiliser application. The shallow loams are prone to a deficiency of potassium (Hall and Raupach, 1963) and had received one cwt. of potassium chloride on each of three occasions - 1962, 1966 and 1967. The sand type had received one application only of the same dosage in 1967. However, the addition of one cwt. of potassium chloride has only a minor effect on wood density (see Chapter 6) so the observed difference in wood density of about 0.050 between the two types is unlikely to be due to fertiliser alone. To explore this point further, maximum, minimum and mean density, averaged over the two replicate plots for each individual growing season, were plotted against age.

FIG. 4-3 Frequency distribution of weighted average density at breast height.



From 1957 to 1966 mean density at both localities and all sites followed a very similar trend of increase with tree age, with density on the loams being consistently less than on the sands (Fig. 4-4). The difference between the soil types was relatively small and more or less constant in each site index class until 1964. Thereafter the differences became considerably greater, tending to be greater with decreasing site index.

The timing of fertiliser applications and thinnings are also shown in Fig. 4-4. Considering the trends in wood density with age, it is evident that application of one cwt. of potassium chloride alone did not affect density. Only thinning had a significant influence on the observed trends. The thinnings in 1966 on the silts and in 1967 on the sands were followed in each instance by a marked fall in wood density in the subsequent year. There was a tendency for the fall in density to be least on the lowest site quality.

The trend in density with age on different site classes is shown very clearly in Fig. 4-5. On the sand there was very close agreement between strata until 1964 (age 10), after which there was a trend for density to be negatively correlated with site index.

If the differences which were evident in 1968 (age 14) were to be maintained with time, there can be no doubt that on these sands there would be statistically (and economically) significant differences in wood density between sites in older stands.

On the other hand, except for one anomalous observation in 1965 in the 40-45 class, the trends in wood density were very similar between sites on the shallow silty loam soils from 1957 to 1968. At this stage there is no reason to expect an effect of site quality on wood density on this soil type.

FIG. 4-4 Trends in mean density on two soil types at Flynn Creek.

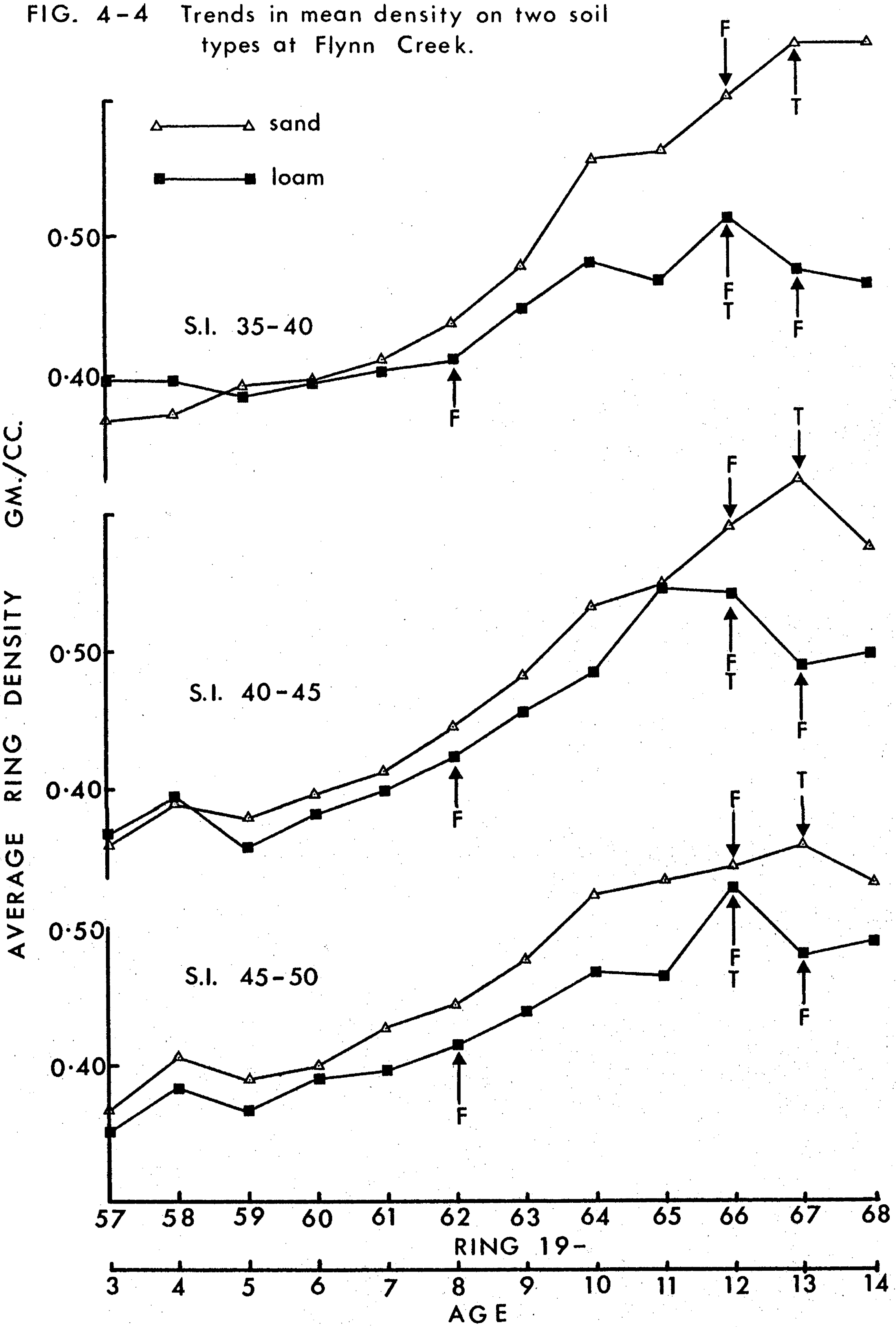
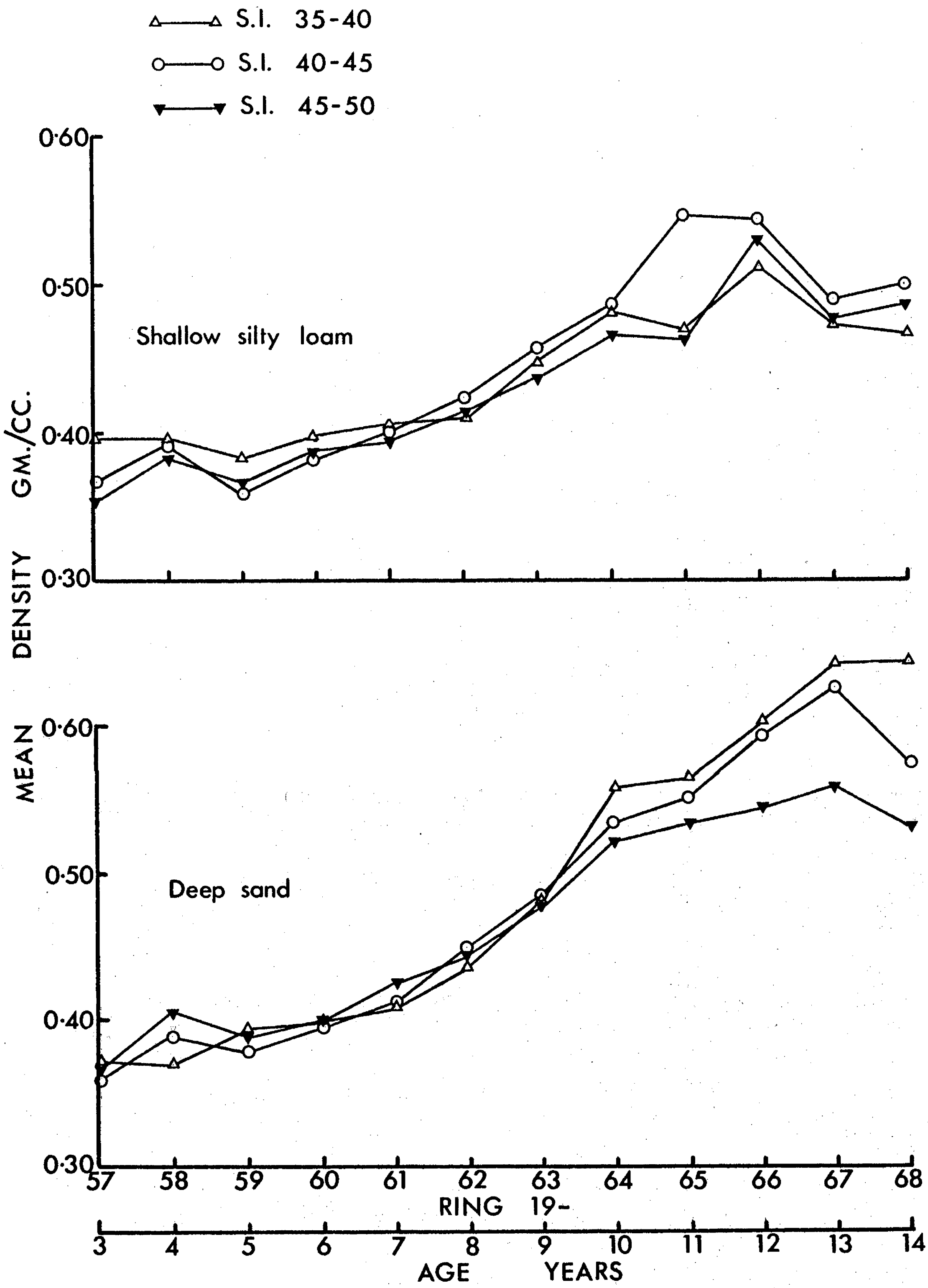


FIG. 4 - 5 Trends in mean density with age for three site classes on two soil types at Flynn Creek.



Maximum ring density tended to be lower on the loams, the differences being more evident in the lower site classes (Fig. 4-6). Minimum density was also lower on the loams but only after 1963 in site classes 40-45 and 35-40; there was also a trend for the differences between soil types to be greater the lower the site quality (Fig. 4-7). When the maxima and minima for each locality are plotted together (Fig. 4-8) it can be seen that minimum density was much less variable than maximum in both areas and there appears to be a relationship between site quality and minimum density developing on the sands but not on the loams. Maximum density was much more variable between sites on the former type. There was no indication at either locality that maximum density was influenced by site index.

Apart from marked falls in maximum density associated with the thinnings in 1967 on the sands and in 1966 on the loams, the observed trends in density maxima and minima appear to be due entirely to seasonal environmental factors. The 1962 fertilisation did not influence these wood properties to a measurable extent. Similar quantities of fertiliser are unlikely to have any effect if applied at a later age, although there might be a cumulative effect of fertilisation in successive years in 1966 and 1967 on the loams. There was no evidence of this in 1968.

The difference in wood density in trees from these two localities is concluded to be due to some inherent factor or factors of the soils and not to the addition of potassium fertiliser.

FIG. 4 - 6 Trends in maximum density on two soil types at Flynn Creek.

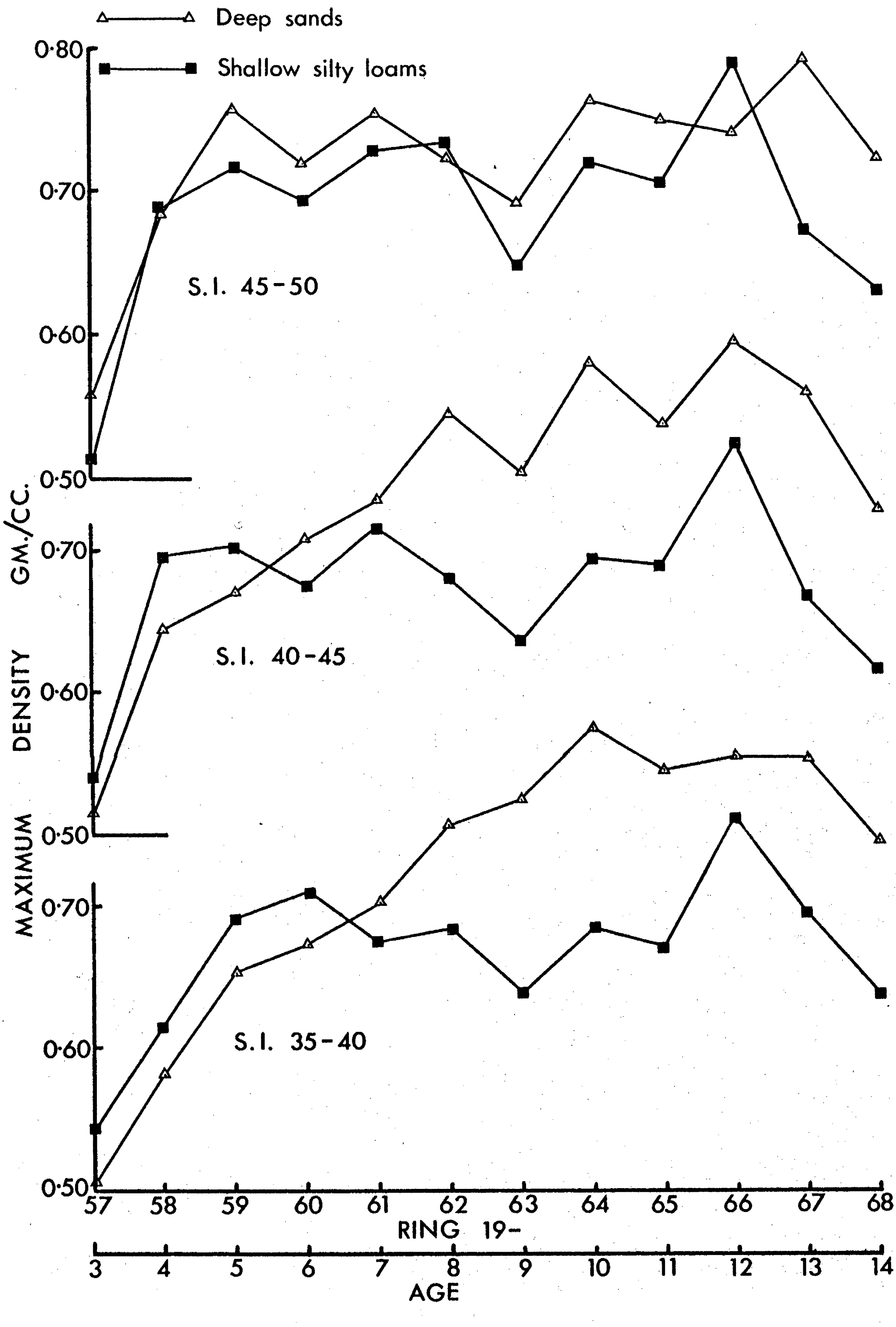


FIG. 4-7 Trends in minimum density with age on two soil types at Flynn Creek.

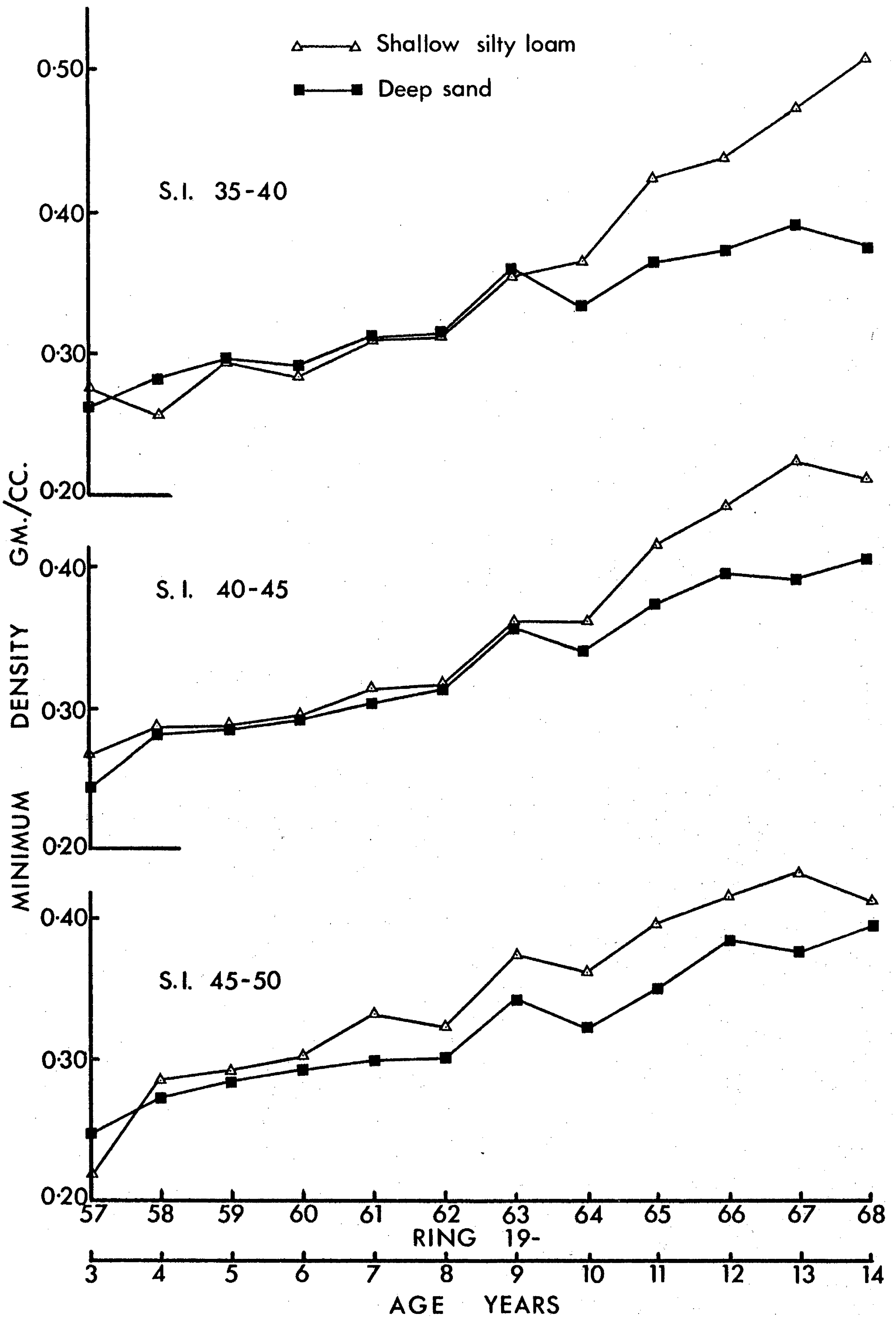
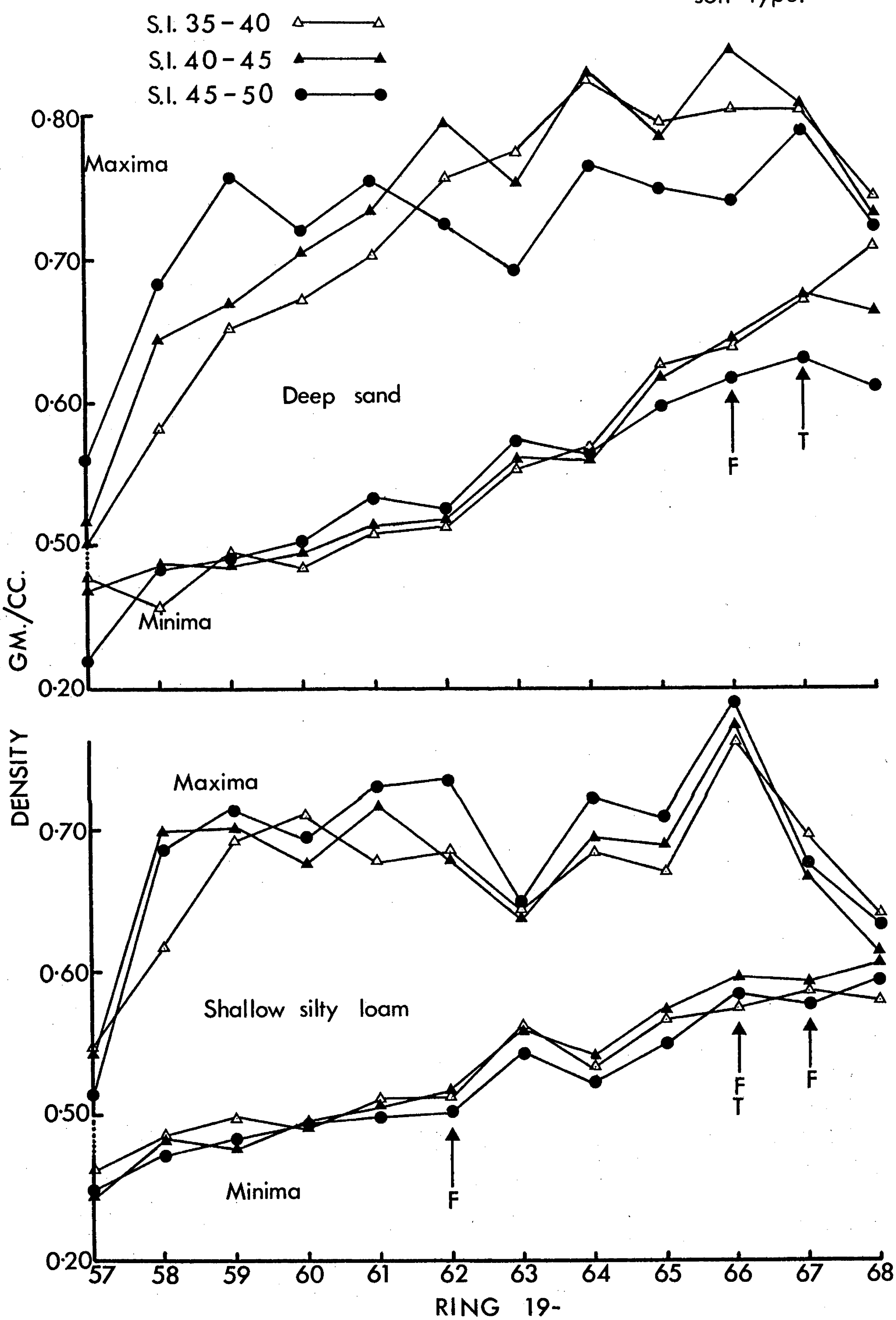


FIG. 4-8 Variation in density maxima and minima with site index and soil type.



Variation in Density Within a Site Class.

The data of Table 4-2 indicate that density is much more variable within sites as well as between sites on the sand soils than on the silty loams. The variability within a site on the sand type was studied further with four plots situated close together in an area of 50-55 site class. The area was chosen for its apparent uniformity of stocking and tree growth. The plots were located about 100 metres apart (Fig. 4-2).

The range of values for plot average weighted density at breast height was 0.025 gm./cc. (Table 4-4), which is the same as the greatest range between replicate plots on any individual site given in Table 4-2.

TABLE 4-4 Wood density and tree growth data for four adjacent plots. Based on 40 trees.

Plot No.	Average Weighted Density (gm./cc.)	Average Tree Vol. (cu.ft.) (a)	Average D.B.H. (in.)	Average Height (ft.)
1	0.479 (b)	4.69	5.51	58
5	0.490	4.42	5.69	54
6	0.480	4.60	5.64	53
7	0.465	5.85	5.89	57

Note: (a) Determined from a local tree volume table compiled by A.P.M. Forests Ltd.

(b) Average of 10 trees.

It is seen that an increase in the number of replicate plots to at least four would be unlikely to modify significantly the conclusions reached in this study. The magnitude of the variation between plots also supports Göhre's (1958) contention that wood density varies as much within sites as it does between sites.

CHAPTER 5

FERTILISER AND WOOD DENSITY (I)

The Belanglo "Close Spacing" Experiment

5.1 Introduction and Review of the Literature.

It has been shown how different levels of wood density in *P. radiata* may be associated with different soil types or variations in site quality on the one soil. Variation in productivity is largely the result of differences in nutrient and/or water availability and whereas it is usually not feasible to modify the latter, the nutrient status of a site can readily be modified. The improvement in tree growth as a result of nutrient amendment amounts to an improvement in site quality so it is logical to expect some influence on the wood properties also.

Interest in forest fertilisation has developed rapidly in recent years partly for economic reasons and partly because increased competition for land has made it necessary to obtain the highest possible yield from available resources. The addition of fertiliser is standard practice in man-made forests in many parts of Australia, for example, the coastal plantations of *P. pinaster* in

Western Australia, some plantations of _P. radiata_ in Victoria and New South Wales and in plantations of _P. elliottii_ in Queensland. In Sweden, application of nitrogen fertiliser from the air is used over extensive areas of native coniferous forest (Hagner, 1967).

The volume of literature dealing with the effects of fertiliser on wood properties is not large, and, in the main, refers to European and North American species. Very little work has been done on the faster growing short rotation exotic conifer crops of the Southern Hemisphere. The published work will be reviewed in two sections: firstly, that concerning the influence of fertilisers on wood density of conifers in general, and secondly, work concerning _P. radiata_ specifically.

Other Conifers.

Most published work on the effect of fertilisers on wood density has dealt with relatively slow growing, mostly uneven aged and sometimes mixed species forests of Western Europe.

Von Pechmann (1958) found repeated fertilisation with calcium ammonium nitrate increased earlywood growth of 90-year old spruce (_Picea abies_ (L) Karst). Cell wall thickness in the latewood zone was also decreased resulting in a decrease in wood density. In a more extensive study published in 1960 von Pechmann and Wutz reported that repeated treatment of a 63-year old stand with lime, phosphate and calcium ammonium nitrate increased earlywood growth, produced thinner cell walls and larger cell diameter in both earlywood and latewood, and a less distinct transition between earlywood and latewood. Wood density was reduced from 0.475 to 0.412. Nitrogen fertilisation of pole-sized Scots pine (P. sylvestris L.) in the Rhine Valley stimulated tree growth for five to six years but did not change wood density or latewood wall thickness. However old pine stands (over 200 years) fertilised with nitrogen, phosphorus and potassium had lower density and thinner cell walls in both earlywood and latewood in the rings formed subsequent to treatment. In another mixed pine-spruce stand there was a sustained growth response for 50 years accompanied by only a slight reduction in wood density (from 0.433 to 0.420 for the pine and from 0.352 to 0.336 for the spruce).

In a later investigation (1962) von Pechman reported an increase in wood density and latewood percentage in a 90-year old spruce stand which had been treated with lime, phosphate and nitrogen.

Tamm, Carbonnier and Hagberg (1960) concluded that wood density and latewood content of slow growing pine in Sweden were not affected by fertilisation but in stands of more normal growth a moderate decrease in density was associated with an increase in growth rate following fertilisation.

However, Ericson (1962) showed that, although in "normal" stands of pine and spruce in Sweden, the wood density was reduced by the addition of fertiliser, on a very poor site the reverse may occur. Thus fertiliser enabled the trees to change from abnormally low density "starvation wood" to the production of normal wood of higher density.

A decrease of density and latewood percentage by one to seven percent for spruce in Norway was recorded by Klem (1964), following treatment with several different fertilisers. The addition of nitrogen fertiliser slightly reduced wood density of Scots pine in Finland (Viro, 1961).

Fertilisation with calcium, nitrogen, phosphorus and potassium was found to reduce wood density of Japanese larch (Larix leptolepis (S. and Z.) Murray) and spruce by two to seven percent (von Seibt, 1963). In a subsequent study von Seibt and others (1968) could detect no effect of nitrogen, phosphorus, potassium, calcium and lupins on the wood density of 38-year old spruce on Luneberg Heath.

Polge (1969) used the X-ray densitometric technique in several studies of the effects of fertilisers on wood density of juvenile maritime pine (P. pinaster Ait.) in the Landes. Phosphorus fertilisers caused a moderate reduction in mean ring density and latewood percentage. Both maximum and minimum density in the ring were reduced, the former to a greater extent, resulting in a small decline in density range.

Several workers have investigated the wood properties of fertilised sugi (Cryptomeria japonica (L.) Don.) in Japan. Ishikawa and Kuroyanagi (1963) reported an increase in the number but not the size of cells per annual increment. Fertilised trees exhibited a greater number of "false rings" than untreated trees. Kano and Nakagawa (1964) found that fertilisation reduced wood density, a greater reduction being associated with repeated treatment. Kuroyanagi (1965) noted a reduction in latewood percentage in fertilised sugi.

In the U.S.A. the first published account of a study of the effect of fertiliser on wood density was that of Wilde and Voigt (1948). They demonstrated a large reduction in density due to fertiliser in seedlings of jack pine (P. banksiana Lamb.). Seedlings grown on coarse sandy unfertilised soil had an average density of 0.41, whereas those grown on a heavily fertilised nursery soil averaged only 0.23 density.

Some years earlier Paul and Marts (1931) had shown how different fertilisers might affect either earlywood or latewood growth separately. In a mature stand of longleaf pine (P. palustris Miller) a complete fertiliser increased earlywood production to a greater extent than latewood, whereas a fertiliser containing nitrogen alone had the reverse effect. No density data were given but it is reasonable to assume that wood density would have been reduced by the complete fertiliser but increased by the nitrogen fertiliser.

Erickson and Lambert (1958) studied the effect of thinning and fertilisation on wood properties of 30-year old Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) in Washington. Using only four sample trees from each of four treatments they concluded that wood density decreased following fertilisation and more so with the combination of fertilisation and thinning.

A three-to-seven percent reduction in wood density and latewood percentage was reported by Williams and Hamilton (1961) for the last two years' growth of ten-year old slash pine (P. elliottii Engelm.) in Georgia. These changes were due primarily to nitrogen; incorporation of phosphorus into the fertiliser mixture had little or no effect. This study is an important one, since it was the first reported anywhere in the literature to employ a good statistical design and adequate sample representation.

Heavy rates of application of nitrogen, phosphorus and potassium to 16-year old loblolly pine (P. taeda L.) in North Carolina resulted in the production of wood with a density 10 percent lower than in unfertilised trees (Zobel, Goggans, Maki and Henson, 1961). These results were confirmed and extended by Posey (1964). Posey determined that potassium in the soils of the experimental area had no detectable effect on wood properties. Nitrogen caused the greatest differences in wood properties, although nitrogen with phosphorus gave a slightly greater response than nitrogen alone. He also concluded that trees with a high initial density showed a greater reduction in density due to fertiliser than trees with a low initial density. Posey was the first worker to attempt to relate wood properties to soil characteristics. Although he had limited success, this approach is considered to be a most promising one and deserves much further work.

A decrease in wood density of western red cedar (*Thuja plicata* D. Don.) as a result of nitrogen application was observed by Wellwood, Ifju and Wilson (1965). The effect was most marked in the lower bole, becoming negligible in the upper bole.

Sastry (1967) noted a small decrease in wood density and latewood percentage in 30-year old Douglas fir following fertilisation with ammonium sulphate or NPK but his study was based on only three sample trees. Williams (1965, cited by Sastry, loc. cit.) also working with Douglas fir, found that ammonium phosphate reduced latewood percentage and density. Nitrate, in combination with phosphate, sulphate, potassium and calcium resulted in an upward trend in density and latewood percentage when applied in several successive years on a poor site. Ammonium nitrate decreased wood density. The results of both these studies must be regarded as indicative only, since both were based on small samples.

To summarise, most evidence favours a small reduction in wood density as a result of the addition of fertiliser to a conifer stand. However, this trend is possibly reversed on the poorest sites. There is also a tendency for the effects of fertilisation to be greater in younger stands. Very little information is available on the long-term effects of fertilisers on wood properties.

Many of the published reports have been based on very small and possibly unrepresentative samples and no attempt has been made, in much of the earlier work, to attach statistical significance to the results. Some studies have been carried out in mixed or uneven aged stands, thus introducing other, complicating, factors to the influence of the fertiliser alone. Most investigations have been concerned with the effect of single fertilisers and very few have attempted to explore the effect of combinations of fertilisers on wood properties. It is entirely possible a detrimental effect of one nutrient could be counterbalanced by the beneficial effect of another.

Except for those in the Southern pines of the U.S.A. all these studies have involved tree crops which are very much slower growing than P. radiata and growing under very different climatic conditions. Thus fertilisers may affect the wood properties of P. radiata to a greater or lesser extent than might be expected from these published reports.

Previous Work on Pinus radiata.

Fielding and Brown (1961) compared the wood density of two groups of 13-year old trees on a poor site in the Australian Capital Territory. One of the two groups of 20 trees was untreated and the other had been treated with five pounds of superphosphate per tree. There was a striking response to the fertiliser in terms of growth rate and general tree health but no effect on wood density, as measured by the average density of bark-to-pith increment cores.

On the other hand, a study of the wood density of P. radiata grown under conditions of phosphate deficiency in New Zealand by Harris (1966) found density of both earlywood and latewood to be higher than normal for the area. Density reverted to normal when the deficiency was corrected.

Gentle, Bamber and Humphreys (1968) examined some wood properties of P. radiata from a fertiliser experiment at Penrose, New South Wales. The trees were 26 years of age, having been fertilised 17 years previously. From a rather small sample of five trees per treatment they concluded that wood density of trees fertilised with either superphosphate or rock phosphate was not significantly different from that of unfertilised trees. However wood from trees receiving superphosphate was significantly higher in basic density than wood from trees receiving rock phosphate.

It is remarkable that this is the full extent of published work in this field considering the economic importance of the species in Australia, New Zealand, South Africa and Chile. All three are concerned with the same element - phosphorus. There is clearly a need for extension of this work to include other fertilisers, to establish the duration of any change in wood density and to determine whether age of a tree, or any other characteristic, such as vigour, affects response to fertiliser.

The following study is the first in a series of four undertaken to examine various aspects of the influence of several fertilisers on wood density of Pinus radiata.

5.2 Experimental Material and Procedures.

The Fertiliser Experiment.

Wood samples for this investigation were collected from seven-year old trees felled during thinning of a fertiliser experiment at Belanglo State Forest, in the Southern Tablelands of New South Wales. The experiment had been established in 1960 by H.D. Waring of the Forest Research Institute, Canberra.

This is a second rotation crop of *P. radiata*, the first crop having occupied the site from 1925 to 1954 and having received no fertiliser treatment in that time. There was poor natural regeneration after clear felling so the area was re-cleared and burnt. The area was replanted in 1960; the initial spacing on the experimental area was 3 ft. x 3 ft., with thinnings at age four to 1200 stems per acre (equivalent to a spacing of 6 ft. x 6 ft.) and again at age seven to 600 per acre. Competition between trees might be expected to become a factor in stand growth at about the time these thinnings were carried out.

Preliminary pot trials by Waring (pers. comm.) indicated growth responses to nitrogen, phosphorus and sulphur, but no response to calcium. The experiment used here compares nitrogen (N), phosphorus (P), sulphur (S) and a combination fertiliser (X) in a factorial design with three replicates. Total quantities of fertiliser applied in the main treatments up to the date of sampling were as follows:

N: 1164 lb./ac. (1305 kg./ha.) of urea

P: 1157 lb./ac. (1297 kg./ha.) of dicalcium phosphate

S: 1921 lb./ac. (2153 kg./ha.) of gypsum

X: 470 lb./ac. (527 kg./ha.) predominantly potassium chloride but with small amounts of Zn, Mn, Na, Mb, Ni, Cu, B, Mg and Fe.

They were applied in five separate dressings beginning three months after planting. This procedure ensured a continuous high level of nutrients. In addition, competing ground vegetation was completely removed by hand for the first two growing seasons. Reports on the growth response to these treatments have been given by Waring (1962, 1967). When sampled for this study trees on the NIL plots averaged about seven feet in height, while on the more successful treatments, such as NP, tree heights were in the vicinity of 25 feet.

Sampling.

Three sample trees were chosen in each plot, stems as close as possible to the mean diameter for the plot being selected, making a total of 144 trees (9 trees per treatment, 16 treatments). A disc was cut from each sample tree at 15 percent of its total height, minor deviations being occasionally necessary due to the presence of a branch whorl. A previous study (Chapter 3) had established the suitability of this sampling approach. Bark-to-bark samples were cut out of the discs and prepared for X-ray densitometric examination as described earlier.

On the density tracings the age segment 1964-66 was chosen for examination, firstly because at least one complete increment for this period was available for each sample and could be recognised with certainty, and secondly, because compression wood was frequently present in rings closer to the pith. Data from one radius only were found to be sufficient in trees of this age in the earlier studies (Chapter 3). Where there was no obvious defect, such as compression wood, on either radius on the tracings, the radius with the lower density was used for measurement. Close examination of the tracings showed that, in spite of the precautions taken in orientation of the samples in the discs, some of the smaller sized samples still contained some compression wood as indicated by anomalous high density areas. In most instances the anomaly was not considered to affect the data significantly, but two samples had to be discarded and new ones cut from material remaining in the discs.

There were very narrow rings in the slowest growing trees. To avoid possible errors in measurement of the areas under the density curves for individual rings, mean density was measured over the whole 1964-66 segment. Maximum density, minimum density and latewood percentage for each sample were also averaged over the three years. The latter was defined as the percentage of wood in the ring with a density greater than 0.468. Radial increment over the three year period was also measured on the tracings.

5.3 Results and Disccussion.

Results.

Factorial analyses of variance by the method of Yates (see Cochran and Cox, 1957) showed wood properties to be affected significantly by all the main factors, N, P, S and the combined fertiliser. Results of the analyses for mean density, latewood percentage and maximum density are summarised in Table 5-1. The latewood percentage data were converted to arcsin values for analysis.

Mean density was reduced by all main factors, the reduction being greatest with P and the combined fertiliser (X). There was no significant first order interaction involving N, but the interactions PS, SX, and PX were significant. In the absence of S or X, P caused a large reduction in mean density, but in the presence of either it had only a moderate effect. Similarly, in the absence of P or X, S caused a moderately large decrease in mean density, but in the presence of either it actually increased density slightly. There was a large reduction in density with X alone, but a negligible effect in the presence of either P or S (Table 5-2).

TABLE 5-1

Analysis of variance - effect of fertiliser treatment on three wood properties for the years 1964 - 1966

Treatment (a)	Mean Squares (b)		
	Mean Density	Latewood Percentage	Maximum Density
Main Factors			
N	0.00450 *	26.70 N.S.	0.01083 *
P	0.03973 ***	1414.84 ***	0.09675 ***
S	0.00383 *	90.75 N.S.	0.00043 N.S.
X	0.01006 **	556.24 ***	0.00003 N.S.
First Order Interactions			
NP	0.00008 N.S.	0.14 N.S.	0.02005 **
NS	0.00005 N.S.	9.72 N.S.	0.00405 N.S.
NX	0.00127 N.S.	31.04 N.S.	0.00454 N.S.
PS	0.01271 ***	276.48 **	0.00757 N.S.
PX	0.00553 *	186.44 *	0.00490 N.S.
SX	0.01188 ***	216.75 *	0.00040 N.S.
Second Order Interactions			
NPS	0.00002 N.S.	10.45 N.S.	0.00527 N.S.
NPX	0.00373 *	44.47 N.S.	0.00215 N.S.
NSX	0.00022 N.S.	13.23 N.S.	0.00019 N.S.
PSX	0.00104 N.S.	70.08 N.S.	0.00104 N.S.
All factors			
NPSX	0.00031 N.S.	12.81 N.S.	0.00462 N.S.
Error Mean Square	0.00081	35.64	0.00215

Note: (a) N = urea; P = dicalcium phosphate; S = calcium sulphate; X = combined nutrient (see text.)

(b) One degree of freedom for each treatment and 30 for error.

TABLE 5-2 First order interactions - mean density (gm./cc.)

	-X	+X	-P	+P	
-S	0.497	0.437	0.512	0.422	-S
+S	0.448	0.450	0.461	0.436	+S
			0.512	0.433	-X
			0.461	0.425	+X

In other words, the influence of P, S or X on wood density is dependent on the availability of other nutrients. If, for example, P were applied to a soil deficient in P but with adequate reserves of S, then there would be a relatively small reduction in the wood density of <u>P. radiata</u> grown on it. But if the soil were deficient in both P and S, the addition of P would produce a large reduction in wood density.

The point is further illustrated by the behaviour of P in the presence and absence of the factor N. In the absence of N there was a marked effect of P in the absence of X, but a small effect in the presence of X. In the presence of N there was a moderate effect of P in both the presence and absence of X (Table 5-3).

TABLE 5-3 Second order interactions - mean density (gm./cc.)

	-N		+N		
	-P	+P	-P	+P	
-X	0.537	0.438	0.487	0.428	-X
+X	0.460	0.438	0.464	0.413	+X

It is seen, then, that the influence of applied fertiliser on wood density depends not on the total amount or type of fertiliser applied, but on the balance of available nutrients after fertilisation. Due to the interactions outlined above it is not possible to quantify effects on wood density of the main factors alone.

Latewood percentage was not significantly affected by N or S (see Table 5-1) but was considerably reduced by P and X. Again, no first order interaction involving N was significant but the interactions PS, PX and SX were all significant. The latewood percentage data very closely paralleled the mean density data and the interpretations of the interactions given for density apply equally to latewood percentage (Table 5-4).

TABLE 5-4 Interaction table - latewood percentage

	-X	+X	-P	+P	
-S	53.5	34.4	57.3	30.6	-S
+S	41.1	36.9	44.2	33.9	+S
			60.0	35.2	-X
			41.5	30.0	+X

Data for the effect of the fertilisers on minimum density are not presented as they bore an even closer resemblance to the mean density data.

Maximum density was markedly increased by P but depressed by N. In the absence of the factor N, P increased maximum density to a moderate extent, but in its presence there was a very large increase. N reduced maximum density in the absence of P, but increased it slightly in the presence of P. (Table 5-5).

TABLE 5-5 Interaction table - maximum density (gm./cc.)

	-P	+P
-N	0.703	0.752
+N	0.632	0.763

The relationship between mean ring density, mean maximum and mean minimum density for each fertiliser combination are shown in Fig. 5-1, the combinations being arranged for convenience in descending order of mean density. The strong associations of mean ring density with minimum density and of maximum density and density range with radial increment (Fig. 5-2) are evident and are borne out by their correlation coefficients in Table 5-6.

TABLE 5-6 Correlation coefficients for several wood and growth characteristics

Relationship	Correlation(a)
Density x radial increment	-0.762 ***
Density x latewood percentage	-0.965 ***
Density x density range	-0.692 **
Density x minimum density	0.963 ***
Density x maximum density	-0.289 N.S.
Radial increment x latewood percentage	-0.826 ***
Radial increment x density range	0.938 ***
Radial increment x maximum density	0.784 ***

Note: (a) Based on 14 degrees of freedom

$R_{.01} = 0.623$ $R_{.001} = 0.742$

FIG. 5-1 Average maximum, mean and minimum density for each treatment combination.

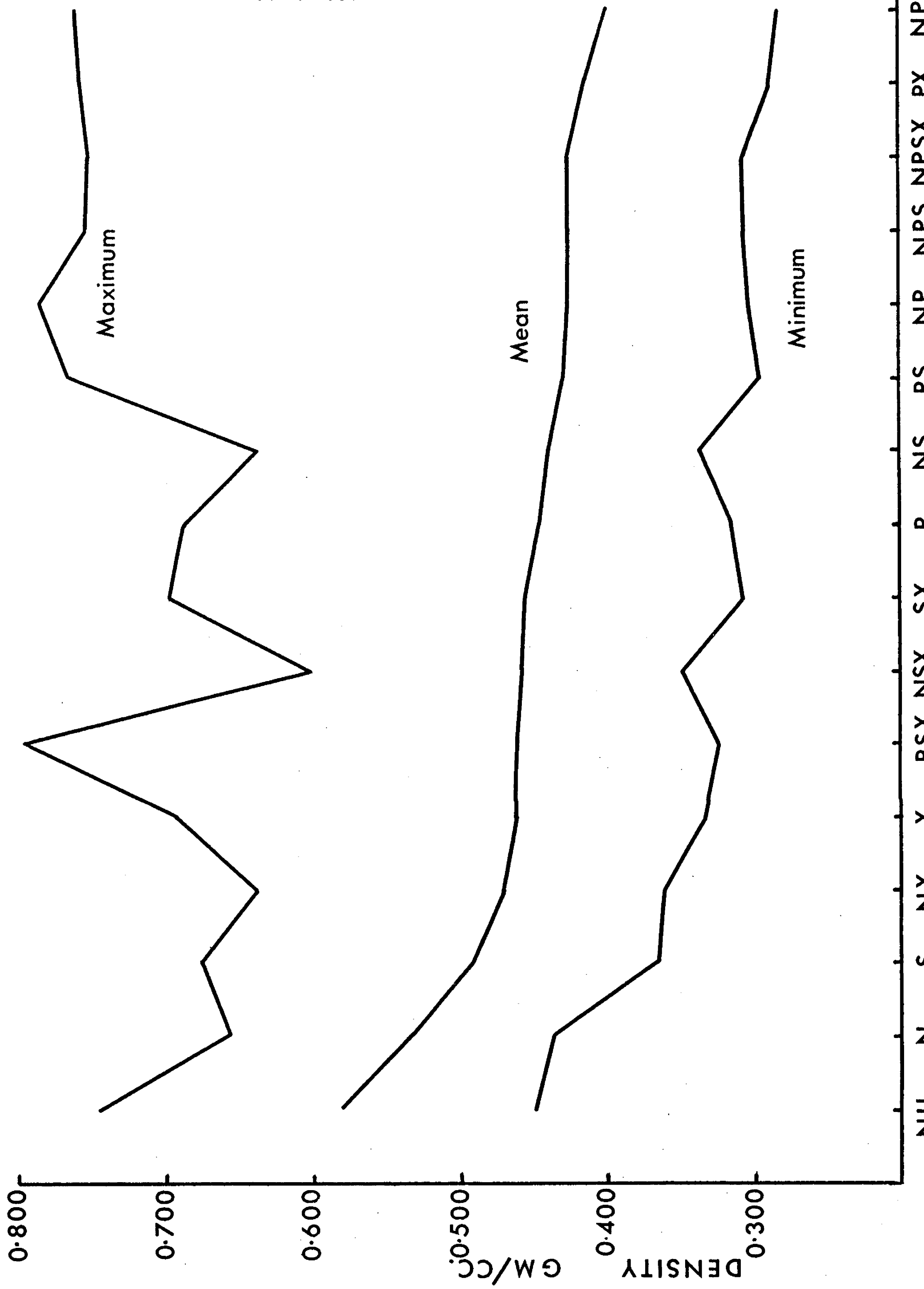
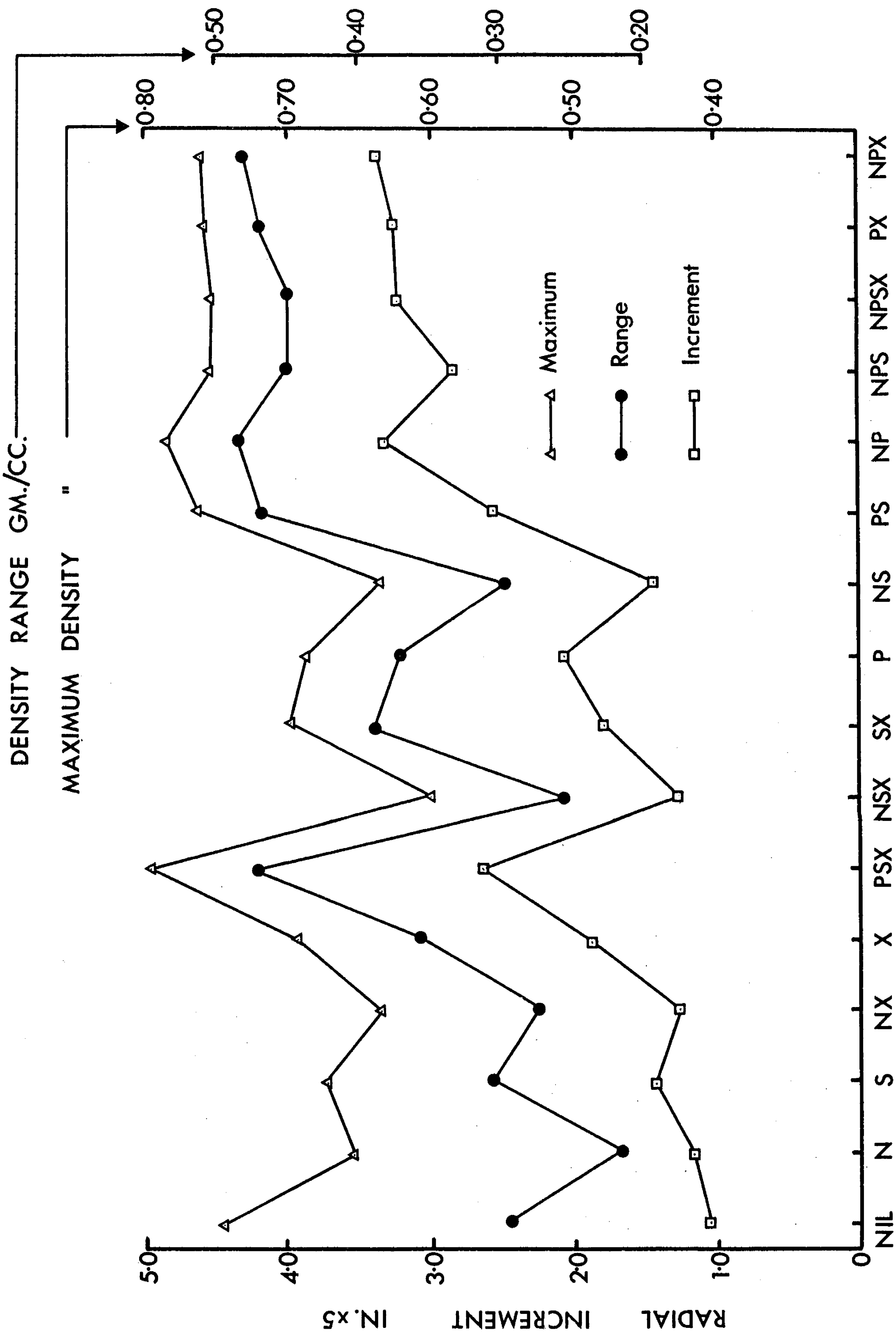


FIG. 5-2 Average radial increment, density maximum and range 1964-66.



A high mean ring density is associated with a high latewood percentage and high minimum density, a low radial increment and a low within-ring density range. There is a tendency (not significant) for a high mean density to be associated with a low density maximum. A high radial increment is accompanied by a low latewood percentage, a high density range and a high maximum density.

Data used to compute these correlations were the means for each treatment combination.

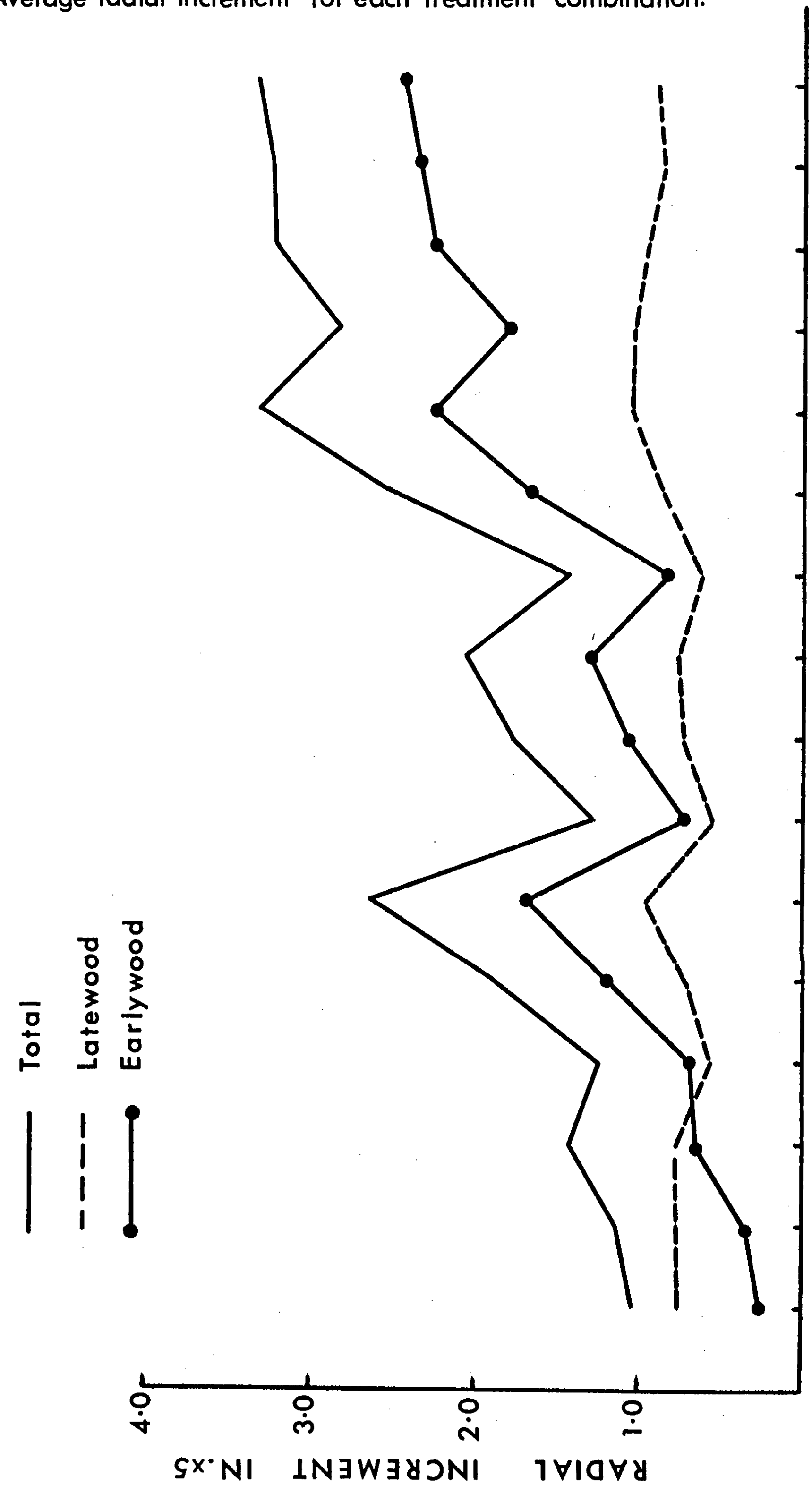
The high negative correlation of mean density with radial increment (Table 5-6) does not imply a direct casual relationship between them. Figure 5-3 illustrates the relative contributions of the earlywood and latewood (as here defined) to the total radial increment over the study period for all treatment combinations. The radial width of the latewood is relatively constant, the observed differences in increment being due almost entirely to varying widths of earlywood. The lower density wood of the faster grown trees is due to an increased development of low density earlywood and not to growth rate *per se*.

Discussion.

Due to the age of the sample trees this study could take only limited advantage of the capabilities of the X-ray densitometric technique. However, the technique has enabled removal of compression wood as a source of error and ensured strict comparability of the mean densities for the growth layers between trees.

There was a dramatic effect on tree growth by some of the fertiliser combinations. For example, estimated dry weight yield at age seven for the NP treatment was eight (8)

FIG. 5-3 Average radial increment for each treatment combination.



times that for the NIL treatment (Waring, pers. comm.). Such differences in growth rate would result in considerable differences in the soil moisture regime between treatments. With rapid growth the demand for water is higher, with consequent earlier exhaustion of available soil moisture supplies. From current hypotheses on the effect of water availability on wood formation (Zahner, 1963) this might be expected to cause an earlier change from low density to high density wood in the faster growing trees. Any such change in the timing of the earlywood - latewood transition was not associated with increased latewood development (Fig. 5-3).

A more rapid depletion of soil moisture and consequent more rapid (and possibly more severe) build up of internal moisture stress would promote the formation of radially flattened latewood cells (Zahner, Lotan and Baughman, 1964). Flattened latewood cells would produce a higher density value than the non-flattened type. This rapid rise in internal moisture stress is likely to have caused a more abrupt transition from earlywood to latewood (Harris, 1955).

Close inspection of Fig. 5-2 reveals an invariable association of high density maxima and high radial increments with the factor P. Since latewood development differed little between treatments it is therefore likely the higher density maxima are due to P and not to growth rate. Trees adequately supplied with P might have a higher net assimilation rate during the latewood phase of growth, resulting in greater cell wall thickening and a consequent higher maximum density.

These consistent increases in maxima by phosphorus are in contrast to the reduction in maxima reported by Polge (1969) for seven-year old P. pinaster in the Landes. This opposite result may be due to physiological differences between the two species or perhaps because Polge sampled at a constant height (40cm.) above ground.

Smith and Morton (1968), comparing the pulp quality of *P. radiata* and *P. elliottii*, found the poorer properties of the latter could be attributed largely to greater differentiation of earlywood and latewood. Density range is a direct measure of this differentiation. Table 5-7 compares the density minimum, maximum and range for *P. radiata* from this experiment with *P. elliottii* from Queensland (Slee, 1968). The latter were nine years old at time of sampling and measurements were made over the last four annual increments. Although these species have a similar mean density, the much wider range of density for *P. elliottii* is clearly demonstrated.

TABLE 5-7 Comparison of parameters of density for *P. radiata* and *P. elliottii*

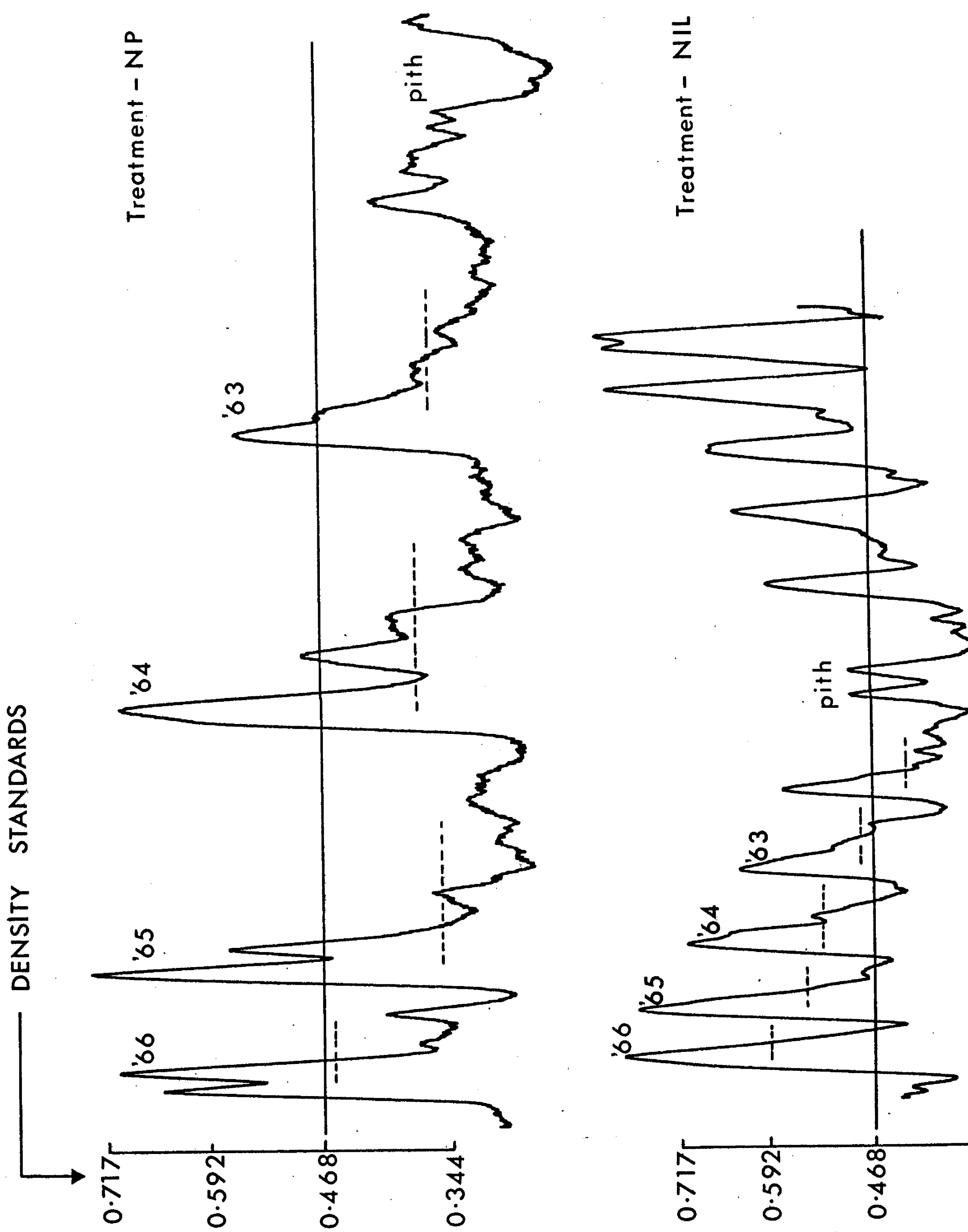
Parameter	P. elliottii (a)	P. radiata (b)
Maximum Density of Latewood	0.860(c)	0.600 - .797
Minimum Density of Earlywood	0.240	0.281 - .450
Density Range	0.620	0.220 - .450
Mean Density	0.470	0.400 - .580

Notes: (a) For five trees

(b) Range of values for the treatment combinations discussed in this study.

(c) All figures in gm./cc.

FIG. 5-4 Typical density curves Belanglo Close Spacing Expt.



Since the same relationships found by Smith and Morton probably hold for within-species variation, the treatment combinations in this study which produced a high within-ring density range would yield a poorer quality pulp. Fortunately, this adverse effect is likely to be offset by the greater proportion of earlywood associated with these treatments, earlywood having, in general, better papermaking properties than latewood (Edlin, 1965).

These changes in patterns of wood density are illustrated by Fig. 5-4. Two density tracings only are shown, one from the NIL treatment and one from the NP combination. Both samples were taken at 15 percent of tree height. It will be noted that, apart from differences in earlywood development and density range, the pattern of increase of mean density outwards from the pith is entirely different, the rate of increase being much greater in the unfertilised tree.

The quantities of fertiliser applied in this experiment are in excess of those used in routine treatments in Australian forestry and the trees were grown under virtually weed-free conditions. Consequently differences in wood density of the magnitude found in this study are unlikely to be realised in routine forestry practice.

The results can strictly be applied only to juvenile _P. radiata_; older trees may not show such marked differences. Nevertheless these results are very important. They have demonstrated, under field conditions, that the influence of a fertiliser on wood density is dependent on the balance of other available nutrients. Some of the conflicting reports in the literature may be due to this effect.

CHAPTER 6

FERTILISER AND WOOD PROPERTIES (II)

The Flynn Creek "KCl" Experiment

6.1 Experimental Material and Methods.

The Fertiliser Experiment.

The stand of *P. radiata* used in this study was planted in 1954 on the Flynn Creek Tree Farm of A.P.M. Forests Pty. Ltd., near Traralgon in Central Gippsland, Victoria. This plantation was established on land formerly used for dairy farming or cattle grazing. The soils were naturally low in potassium and were further depleted by the removal of hay and dairy produce (Drake and Kehoe, 1954). Such 'induced' potassium deficiency has also been observed in New Zealand (During, 1959).

In late 1958 it was established that *P. radiata* in the Flynn Creek area was deficient in potassium (Hall and Purnell, 1961) and in December, 1960, an experiment was laid out to investigate the effect of several levels of potassium fertiliser on tree growth. The fertiliser, as potassium chloride (KCl), was applied broadcast at the rates of 0, 1/9, 1/3, 1, 3 and 9 cwt. per acre. The experimental design was a 6 x 6 Latin square. Initial results for this experiment have been reported by Hall and Raupach (1963).

The 1/9 and 1/3 cwt. treatments produced growth responses closely paralleling the 0 and 1 cwt. treatments respectively, so were not sampled for this study. The four treatments sampled were, therefore, 0, 1, 3, and 9 cwt. KCl per acre. Volume yields to a three-inch top diameter limit up to 1967 for these four treatments are given in Table 6-1 (Hall, pers. comm.).

TABLE 6-1 Average volume production 1960 and 1967

Fertiliser Level cwt./ac.	Standing Volume 1960 cu. ft./ac.	Standing Volume 1967 + thinnings 1966 cu. ft./ac.
0	417	2175
1	378	2565
3	429	3026
9	392	3214

Apart from pruning of dead branches up to seven feet from the ground, the only other treatment received by the plots was a thinning in late 1965, ie., the 1966 growing season. Each treatment was reduced to approximately equal basal area. There was some variation in the average number of stems per acre between treatments when the initial fertiliser applications were made (see Table 6-2).

TABLE 6-2 Average stocking during the study period

Fertiliser Level cwt./ac.	Average Stocking 1960 Stems/ac.	Average Stocking 1967 (after thinning) Stems/ac.
0	818	457
1	745	400
3	787	409
9	709	423

Methods.

In late August, 1967, ie. at tree age 13, samples were obtained from three trees in each of the six replicate plots - a total of 72 trees. The three trees per plot were selected as follows :

A class: the largest diameter tree on the plot

B class: the tree closest in diameter to the mean diameter for the plot

C class: the smallest diameter tree on the plot

One wood sample per tree was removed at about breast height, care being taken not to locate the sample closer than six inches from a branch whorl. The breast height sampling position was considered suitable in view of the height of the trees (about 50 feet) and the small differences in height between treatments.

For the A and B class trees one bark-to-pith sample was cut out with the Solo chainsaw tree sampler, usually on the northern side of the trunk as there was a general west-east stand lean. The samples were oriented in this direction both to minimise the likelihood of inclusion of compression wood in the sample and to provide a more representative ring width than would have been expected on the shortest radius (the western side of the trunk). The C class trees were too small to attach the chainsaw guide unit securely, so they were felled and a disc cut out at breast height. These field samples were prepared for X-ray examination as previously described (p. 24).

On the density tracings measurements were made on each ring from 1960 to 1966 inclusive. For each ring maximum density, minimum density, mean ring density and density range were calculated. Latewood percentage was measured as the percentage of wood in a ring with a density greater than 0.468 gm./cc.

6.2 Results.

The variation in average stocking between treatments shown in Table 6-2 (and the larger variation between individual plots) might also have influenced wood properties. This was examined by multiple regression analysis which established that variation in individual plot response was an insignificant part of the total variance in wood density. The effect of fertiliser on wood density therefore was analysed as a randomised block design for each year from 1960 to 1966 and for the 1962-66 averages.

Mean ring density, minimum density in a ring and latewood percentage were all lower in the fertilised treatments than in the unfertilised controls, and there was a slight tendency for maximum density to be higher in the fertilised treatments.

Mean density was 9 percent lower in the 9 cwt. treatment than in the control in the first year after fertilisation, this being statistically significant (Table 6-3). The percentage reductions in the following years were 14 in 1963, 12 in 1964, 14 in 1965 and 8 in 1966, the latter being non-significant, statistically. The response in the 3 cwt. treatment was almost as great, the comparable figures for the years 1962 to 1966 being 6, 8, 11, 12 and 7 percent. One cwt. of KCl reduced mean density only to a small extent from 1962 to 1965 but actually increased it slightly in 1966. The reductions were 1, 4, 7 and 3 percent respectively. Taking the period 1962 - 1966 as a whole, 9 cwt. of KCl reduced mean density by 11 percent (one percent level of significance), 3 cwt. reduced it by 8 percent (five percent level of significance) and 1 cwt. reduced density by 1.5 percent (non-significant).

TABLE 6-3 Effect of KCl on mean density

Fertiliser Level cwt./ac.	Annual Treatment Means					
	1960(a)	1962	1963	1964	1965	1966
9	0.403	0.405*	0.402**	0.453*	0.460**	0.510NS
3	0.402	0.419NS	0.429*	0.459*	0.468*	0.515NS
1	0.412	0.438NS	0.451NS	0.479NS	0.515NS	0.572NS
Control	0.407	0.444	0.468	0.517	0.533	0.553

Note: (a) Treatment means for 1960 (before fertilisation) included for comparison. No worthwhile improvement in results was obtained from a covariance analysis on these small initial differences.

Latewood percentage (Table 6-4) was affected in much the same way as mean density, as might be expected from the close correlation between the two parameters. The average latewood percentage over 1962 - 1966 was 49.6 in the controls, 49.4 for 1 cwt., 38.0 for 3 cwt. (significantly lower than the controls at the one percent level) and 34.4 for 9 cwt. of KCl (significant at the one percent level).

TABLE 6-4 Effect of KCl on latewood percentage

Fertiliser Level cwt./ac.	Annual Treatment Means					
	1960	1962	1963	1964	1965	1966
9	28.5	26.5*	24.7**	37.2**	34.8*	48.9*
3	25.7	26.9*	28.8*	40.4**	40.8NS	52.9NS
1	26.8	39.5NS	39.6NS	48.6NS	53.5NS	65.9NS
Control	26.9	36.8	42.1	57.9	50.6	60.8

Minimum ring density was lower at all levels of fertiliser, the effect becoming greater with increasing quantity applied (Table 6-5). During the five years following fertilisation, average minimum density in the controls was 0.384, one cwt. of KCl reduced it to 0.367, 3 cwt. to 0.334 and 9 cwt. to 0.313 (both the 3 and 9 cwt. treatments were significantly lower than control at the one percent level).

TABLE 6-5 Effect of KCl on minimum ring density (gm./cc.)

Fertiliser Level cwt./ac.	Annual Treatment Means					
	1960	1962	1963	1964	1965	1966
9	0.295	0.280**	0.310**	0.296**	0.337**	0.344*
3	0.299	0.312NS	0.334**	0.323**	0.351**	0.348**
1	0.302	0.322NS	0.358NS	0.349NS	0.391NS	0.416NS
Control	0.309	0.338	0.370	0.374	0.411	0.427

Due mainly to these lower density minima, density range was increased by the fertiliser, the 9 cwt. treatment again having by far the greatest effect.

Average density range for the five years following fertiliser application was 0.326 in the control, 0.368 for the 1 cwt. treatment, 0.388 for 3 cwt. and 0.417 for 9 cwt. KCl per acre. Details for the individual years, including significance levels, are given in Table 6-6.

TABLE 6-6 Effect of KCl on density range (gm./cc.)

Fertiliser Level gm./cc.	Annual Treatment Means					
	1960	1962	1963	1964	1965	1966
9	0.387	0.485**	0.348*	0.419**	0.372**	0.459**
3	0.415	0.429NS	0.340*	0.358NS	0.380**	0.431**
1	0.418	0.430NS	0.317NS	0.342NS	0.347NS	0.404*
Control	0.388	0.383	0.278	0.318	0.315	0.337

6.3 Discussion.

General.

From the results presented it is evident that the application of KCl to this potassium deficient site markedly influenced wood density. The reduction in mean density was largely a result of increased earlywood growth, which is in agreement with the results of several similar investigations reviewed by Klem (1968). The increase in earlywood growth was directly related to the amount of KCl added (see Table 6-7).

TABLE 6-7 Average earlywood radial increment (inches x 5)

Fertiliser cwt./ac.	Growing Season 1960	1961	1962	1963	1964	1965	1966
0	1.37	1.01	0.65	0.43	0.26	0.29	0.22
1	1.12	0.82	0.59	0.51	0.35	0.31	0.18
3	1.25	0.95	0.82	0.67	0.52	0.51	0.31
9	1.19	1.00	0.89	0.80	0.65	0.62	0.35

A further, but small, part of the reduction in mean density could be attributed to the changes in minimum ring density associated with fertilisation. The relative importance of the latewood percentage and minimum density components of mean ring density was determined by multiple regression analysis for all trees in the control and 9 cwt. KCl treatments, using the 1962 - 1966 mean data. As for the Belanglo Close Spacing Experiment (Chapter 5), latewood percentage again was found to be by far the best predictor of density, but was a better predictor for the fertilised than for the unfertilised trees (Table 6-8).

TABLE 6-8 Correlations between mean ring density and its component factors

Factor	9 cwt. KCl		Control	
	R	R^2 (a)	R	R^2
LW (b)	0.960	0.920	0.862	0.741
LW + MIN	0.975	0.950	0.957	0.900
LW + MIN + MAX	0.981	0.962	0.966	0.932

Note: (a) R - multiple correlation coefficient

R^2 - coefficient of determination

(b) LW - latewood percentage

MIN - minimum ring density

MAX - maximum ring density

Latewood percentage is able to explain a lower proportion of the variation in density in the control trees because in their narrower rings the shape of the transition curve from low to high density has a significant effect on mean density for the ring (see also Chapter 2.3). In contrast to this, the greater earlywood growth of the fertilised trees obscures the influence of the transition curve.

The importance of minimum density as a component of mean density depends on the degree to which it is a measure of average earlywood density. It might be expected that in narrow rings it would be a better measure than in rings with wider, and more variable, earlywood growth and this is supported by the data in Table 6-8. In both groups of trees the addition of maximum density to the regression results in only a very small increase in the explainable variance in density.

Whereas there was a general trend for mean density to increase from 1960 to 1966 (age 6 to 12) in the way characteristic of most conifers, even at this age there was a strong overriding influence of seasonal growing conditions. It is generally accepted that latewood development is strongly influenced by late summer-early autumn rainfall. Due to the high correlation between latewood percentage and mean ring density, density is also influenced by rainfall over that period. Over the seven years 1960-66 at Flynn Creek, density was significantly correlated with total rainfall for the months of February, March and April. The simple correlation coefficients were -

Control	-	0.810*,
1 cwt.	-	0.830*,
3 cwt.	-	0.872*,
9 cwt.	-	0.892**.

Duration of the Fertiliser Response.

The duration of the effect of KCl application on wood density and growth is of particular interest. A growth response to potassium has been observed to last for up to 20 years (Heiberg, Madgwick and Leaf, 1964) on sandy soils in northeastern U.S.A. The increments for 1966 given in Table 6-7 and the non-significant differences in mean density in 1966 between the control and the 3 and 9 cwt. treatments suggest that the response due to fertiliser was waning after 5 years. These results, however, are largely due to an interaction of fertiliser and seasonal growing conditions, namely, a very dry spring in the 1966 season (see Appendix II). While radial latewood increment was comparable in 1964, 1965, and 1966, earlywood growth was much reduced in 1966, resulting in higher mean density for that year in all treatments. The fertilised plots were proportionately more affected than the controls (see Table 6-7) so their mean ring density rose more than in the controls. There is, then, good reason to suppose that the differences in density between the fertilised and unfertilised trees would have been maintained in 1967 with more favourable growing conditions.

In 1968 there was some evidence from foliar analysis (Hall, pers. comm.) that the control trees were beginning to pick up potassium from the fertilised plots, therefore limiting the usefulness of this experiment to the period 1960 - 1967.

Influence of Competition Within the Stand.

Increasing variability of the density data was another factor contributing to the lack of statistically significant differences in density between treatments in 1966. The standard deviations of the individual tree values (and the replicate plot means) rose in every year over the period studied. This increase in variability is attributed to the onset of competition between the trees with a resulting tendency for the density of the wood in any growth layer to reflect the competitive position of the tree in the stand.

Due to the inverse correlation of wood density with tree size (p. 39), the dominant trees have the lowest wood density, the codominant trees tend to be of intermediate density and the suppressed trees have the highest wood density. The period 1960 - 1966 coincided with the emergence of this pattern for this stand (Table 6-9).

TABLE 6-9 Variation in wood density with tree class

Tree	Overall Mean Density (gm./cc.)						
Class(a)	1960	1961	1962	1963	1964	1965	1966
A	0.421	0.421	0.422	0.422	0.443	0.432	0.490
B	0.403	0.411	0.428	0.440	0.484	0.509	0.534
C	0.394	0.411	0.429	0.449	0.503	0.541	0.587

Note: (a) See Methods

In 1960 the general trend was for the A class trees to have the highest density and the C class the lowest. At age six there would have been little competition between trees and any variation in wood density would have been due to genetic differences and chance site factors.

The observed trend in 1960 is probably a result of the unsuitability of the breast height sampling point in trees of that age and size (see Chapter 3). Height at age six would have ranged from roughly 15 feet to 25 feet, consequently the wood density at breast height would vary according to tree class as shown in Table 6-9.

In 1962 the pattern began to change and by 1964 there was a strong tendency for wood density to be inversely related to tree class. The pattern was the same in all treatments but was best developed in the control and 9 cwt. KCl treatments.

It is worthy of note that the development of the wood density - tree class pattern typical of mature conifers coincided with the time of canopy closure.

As there could have been a relationship between tree class, wood density and response to fertiliser, the data for average density 1962-1966 were analysed further as a split-plot design testing each level of fertiliser separately against the control. The results of the analysis of variance are presented in Table 6-10.

There was a relationship between tree class and wood density, but no interaction of tree class with fertiliser, as shown also by Williams and Hamilton (1961) in 10-year old slash pine (*P. elliottii* Engelm.).

TABLE 6-10 Analysis of variance - effect of fertiliser and tree class on wood density (1962 - 1966 tree averages).

Source of Variation	Degrees of Freedom	Mean Square	F-ratio
1 cwt. Fertiliser	1	0.00054	0.19NS
Error (a)	5	0.00280	
Class	2	0.00160	1.07NS
Class x Fertiliser	2	0.00150	1.00NS
Error (b)	20	0.00149	
3 cwt. Fertiliser	1	0.01373	3.25NS
Error (a)	5	0.00422	
Class	2	0.00612	3.50*
Class x Fertiliser	2	0.00008	0.04NS
Error	20	0.00175	
9 cwt. Fertiliser	1	0.02486	8.35*
Error (a)	5	0.00298	
Class	2	0.01027	6.09**
Class x Fertiliser	2	0.00231	1.37NS
Error (b)	20	0.00169	

Individual Tree Response to Fertiliser.

Posey (1964) found that trees with a high initial wood density showed a greater reduction in density after fertiliser application than trees with a low initial wood density. To test this hypothesis average density before fertilisation (1960-1961) was plotted against average density after fertilisation (1962-1966) for each tree in each of the four treatments and the linear regression calculated. The regressions for the four treatments are presented in Figure 6-1 which shows a trend for trees with an initial higher density to be less affected by the addition of fertiliser. For example, a tree with a density of 0.350 before fertilisation would be 14 percent lower than a similar control tree after fertilisation with 9 cwt. KCl, 10 percent lower with 3 cwt. and 3 percent lower with 1 cwt. KCl. The corresponding figures for trees which were 0.450 before fertilisation are 7, 6 and 2 percent.

Zobel and others (1961) suggested trees may show individual wood property responses to fertiliser application. There is evidence for several species, including P. radiata, of heritable differences in ability to make use of nutrients in terms of tree growth. Different physiological responses to nutrient level might well influence wood formation.

In this study a tree could be found in all fertiliser treatments to illustrate any possible combination of response with initial density, but it cannot be inferred that this is evidence for variation in individual response to fertiliser since a similar degree of variation could be found among the control trees over the same period. Figure 6-2 illustrates the type of variation encountered. For clarity of presentation the control and 9 cwt. treatments only are considered. The mean density for each year from 1960 to 1966 is shown for the six B class trees. While the general trend in both graphs is for trees with a high (or low) initial density to remain high (or low), as indicated previously, there is considerable variation from year to year and exceptions can be found, notably tree 351 (9 cwt.). This tree might be a genotype which tends to produce high density wood in the presence of more than adequate supplies of potassium.

FIG. 6-1 Effect of initial wood density on density response to fertiliser.

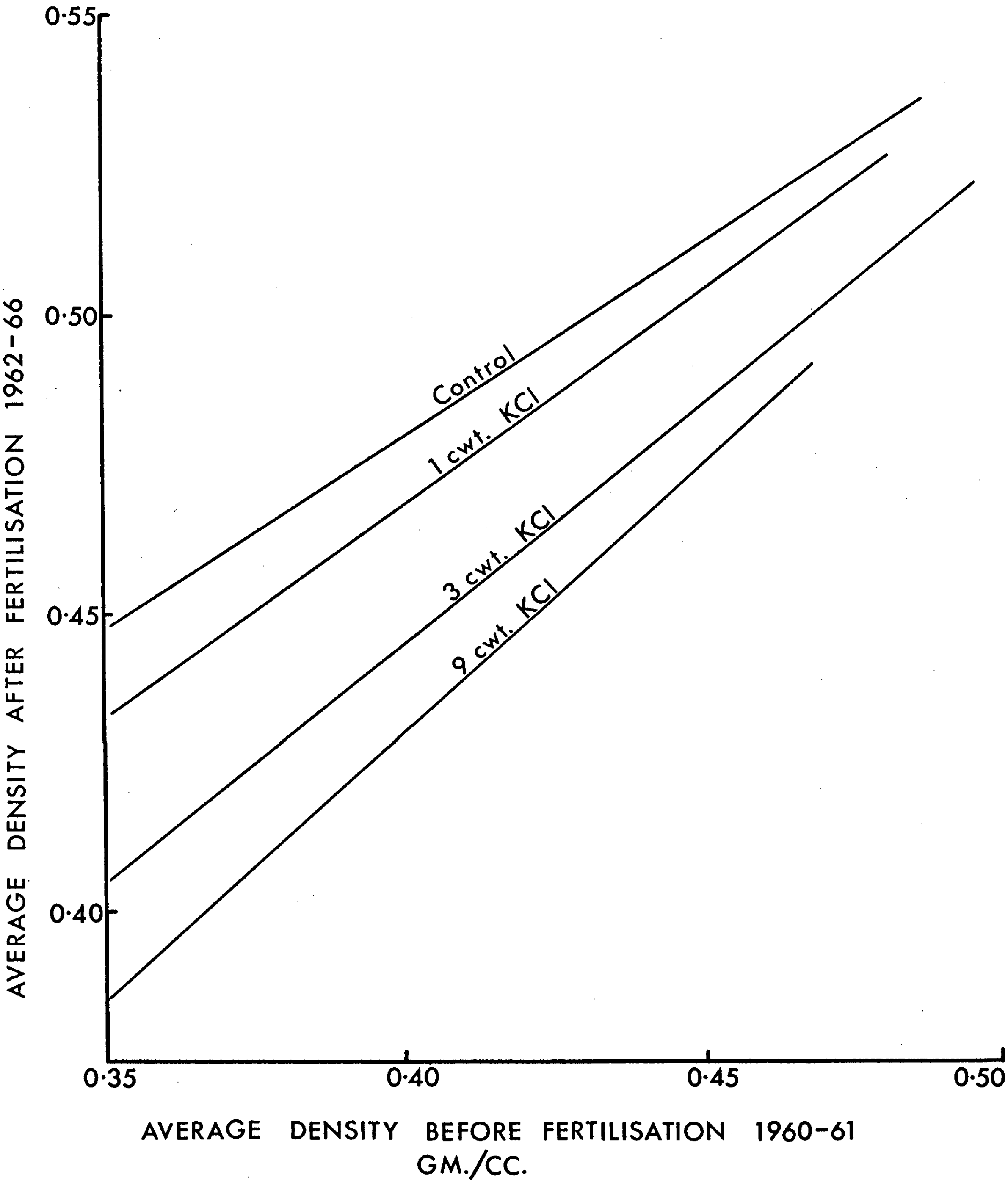
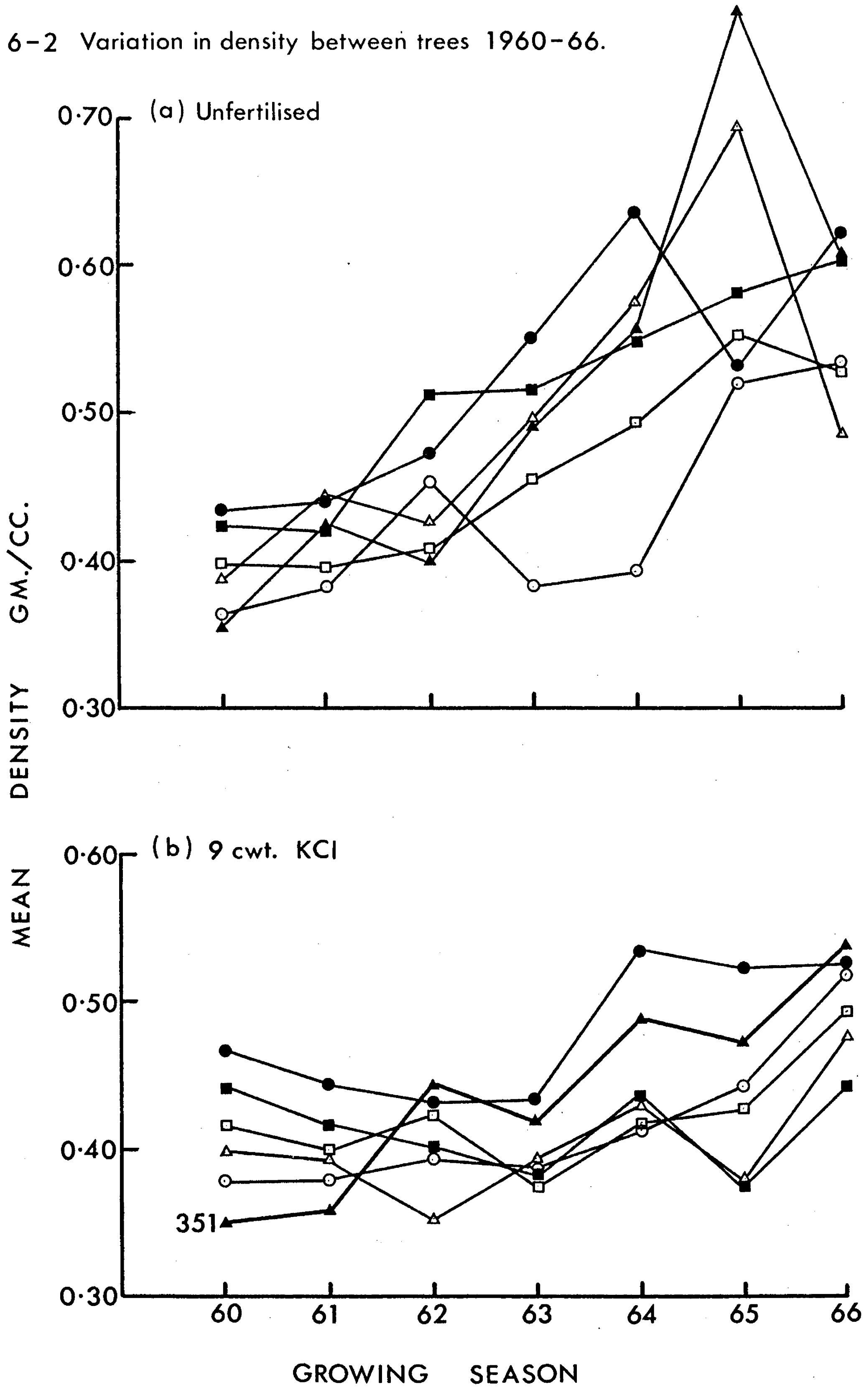


FIG. 6-2 Variation in density between trees 1960-66.



An influence of potassium alone on wood density has not been demonstrated previously. Fertilisation with potassium chloride in this study resulted in decreases in density and latewood percentage, the decrease being greater with larger quantities of fertiliser. The addition of quantities greater than 3 cwt. did not produce correspondingly greater wood property responses. All tree sizes from the largest to the smallest in the stand responded to the fertiliser in a similar manner.

CHAPTER 7

FERTILISER AND WOOD DENSITY (III)

The Flynn Creek "NPK" Experiment

7.1 Experimental Material and Methods.

The Fertiliser Experiment.

The third fertiliser experiment investigated in this series was established in an eight-year old stand in December, 1962, at the Flynn Creek Tree Farm. It was adjacent to the KCl experiment (Chapter 6) and in trees of the same age and stand history. The fertiliser experiment was a 2 x 3 factorial design replicated in three blocks. The main treatments were ammonium nitrate (N), superphosphate (P) and potassium chloride (K), applied broadcast at 440 lb./acre (500 kg./ha.). As in the KCl experiment the only other treatments carried out on the plots were low pruning of dead branches and a thinning in December, 1965, at age 11 years.

In terms of volume growth there was a response to N and K only, the increase in volume over the untreated controls from 1962 to 1967 being 22 percent and 38 percent respectively (Hall, pers. comm.). As in the KCl experiment there was considerable variation in stocking between plots, mean stocking for individual treatments ranging from 627 per acre to 813 per acre.

Sampling.

Three sample trees were used from each of the 24 plots in the experiment - 9 trees per treatment combination and 72 trees in all. The three trees chosen in each plot were the three closest in diameter to the mean diameter for the plot. This sampling procedure was adopted mainly to reduce the large variation in density values between trees in a plot which had become evident in the KCl study. It was also hoped that sampling trees in one size class would minimise variation in the competition factor between trees and so obtain more precise information on individual tree responses to fertiliser.

A disc two inches in thickness was removed from each tree at the mid point of the internode in which the breast height point fell. In addition to the breast height samples, discs from the butt and then every 10 percent of tree height up to the 80 percent point, were removed from each of the nine trees in the control and the NPK fertiliser combination.

The samples to be used in X-radiography were cut from the discs and prepared for analysis by the procedures standardised in this study (p. 24).

On the density tracings for the breast height samples mean density, minimum density and maximum density were measured on each ring from 1960 to 1967 inclusive. Latewood percentage was measured in each ring at four levels on the density curve, equivalent to density values of 0.35, 0.45, 0.55 and 0.65 gm./cc. (see Chapter 2). These data are henceforth referred to as LW 35, LW 45, LW 55 and LW 65.

For the 18 trees used in the within-tree density study, mean density, maximum and minimum density only were measured for all rings present on the tracings.

Analysis of the Data.

Since the samples were cut from discs, there were two bark-to-pith tracings at each sampling point. Data from the same ring on opposite radii were averaged before analysis.

For the breast height data the standard method of factorial analysis was employed.

For the within-tree study the data were processed on the A.N.U. computer by the programs DENDRY and VOLS (see Appendix I) which calculated the following:

(a) weighted whole tree density for the tree in 1967, and as it was in 1966, 1965, 1964, 1963 and 1962

(b) weight (approx. air dry) of each annual sheath from 1962 to 1967

(c) total volume (to a three-inch top diameter limit) and volume of earlywood and latewood for each sheath, using a density level of 0.468 as the earlywood-latewood boundary.

7.2 Results and Discussion : The Breast Height Data.

The Main Study.

Preliminary analysis established that the variation in stocking between plots was not associated with variation in wood properties before or after fertilisation. No allowance was made in the analysis of variance for the variation in wood properties between treatments prior to 1963, since the differences were very small.

All three fertilisers modified wood properties in some way. Although the treatments were applied in December, 1962, halfway through the 1963 growing season, there was an immediate effect of N on wood properties. The influence of P and K did not become evident until the 1964 season. Table 7-1 lists the variance ratios of the treatments which reached or approached statistical significance.

TABLE 7-1 Summary of analyses of variance NPK experiment.

Parameter	1963	1965	1965	1966	1967
Maximum Density	N 11.04**	P 6.29*	P 8.01*	-	-
Minimum Density	-	K 4.84* N 4.60*	K 11.32**	K 14.29** NK 10.94**	K 12.22** NK 5.45* PK 8.50*
Mean Density	N 4.01NS	N 3.27NS K 6.48*	N 2.29NS K 6.53*	K 17 91** NK 5.50*	K 7.13* N 3.14NS
Mean Latewood Percent.	N 8.87**	K 4.62* N 3.42NS	K 5.05* N 2.82NS	K 12.29** NK 6.11*	K 5.22* N 2.40NS

Maximum density was depressed by N in 1963, but thereafter the influence of N on maxima was negligible. In 1964 and 1965 maximum density was increased by P (Table 7-2), a rather unexpected result, as P did not affect diameter or volume increment and had very little effect on any other of the wood properties studied in this experiment. Thus it is possible to obtain a specific effect of a nutrient on wood density which is not associated with a change in growth rate. The influence of P declined rapidly after 1965 and had disappeared altogether in the 1967 ring.

TABLE 7-2 Effect of fertilisers on maximum density (gm./cc.)

1963		1964		1965		1966	
+N	0.570	+P	0.742	+P	0.716	+P	0.748
-N	0.617	-P	0.698	-P	0.676	-P	0.735

These results are in good agreement with those of the the Belanglo Close Spacing experiment. However, the duration of the depression of maxima by nitrogen was shorter at Flynn Creek as the fertiliser was applied on one occasion only instead of several as at Belanglo.

The transient influence of N on wood properties was again evident in the minimum density data. Minima were depressed in 1964 by both N and K to about the same extent. In 1965 the reduction due to K was greater but the effect of N had declined considerably. In both 1966 and 1967, N and K interacted. In the presence of N, K had very little effect on minimum density, but produced a large reduction in its absence. Alternatively, N produced a moderate reduction in minima in the absence of K, but a small increase in the presence of K (Table 7-3).

In 1967, P and K interacted. In the presence of P, K again had little effect on minima, but caused a large reduction in its absence. The factor P caused a small increase in minima in the presence of K, but a small reduction in its absence.

TABLE 7-3 Effect of fertilisers on minimum density NPK experiment (gm./cc.)

1964		1965		1966			1967		
+N	0.307	+N	0.330		+K	-K		+K	-K
-N	0.324	-N	0.344	+N	0.341	0.346	+N	0.343	0.350
				-N	0.317	0.389	-N	0.339	0.373
+K	0.306	+K	0.325						
-K	0.325	-K	0.349				+P	0.350	0.353
							-P	0.333	0.370

As a result of these effects on density maxima and minima, density range tended to be increased by all three factors.

In the season of fertiliser application (1963) only N influenced mean density, causing a slight reduction. This small reduction by N persisted to the end of the period of study; however, it was never statistically significant.

As expected from the results of the adjacent KCl experiment (Chapter 6) K significantly reduced mean density from 1964 to the last year studied. There was no evidence of a decline in its influence on density in 1967 (Table 7-4).

TABLE 7-4 Effect of fertilisers on mean density NPK experiment (gm./cc.)

1963	1964	1965	1966			1967
+N 0.445	+N 0.469	+N 0.441		+K	-K	+N 0.445
-N 0.460	-N 0.487	-N 0.458	+N	0.482	0.499	-N 0.466
			-N	0.473	0.535	
	+K 0.465	+N 0.435				+K 0.440
	-K 0.491	-N 0.464				-K 0.471

Nitrogen and potassium interacted in 1966. Potassium caused a large reduction in mean density in the absence of N, but only a small reduction in the presence of N.

Latewood percentage was reduced at all four levels in the ring by K, and to a lesser extent by N. The reductions were generally statistically significant only for LW 35 and LW 45 (Table 7-5).

TABLE 7-5 Summary of analyses of variance latewood percentage.

Parameter	1963	1964	1965	1966	1967
LW 35	N**	N*	K*	K** NK*	K**
LW 45	-	K* N*	-	K** NK** NP* NPK*	-
LW 55	-	-	-	K*	-
LW 65	N** NK*	-	-	-	-

It is interesting that so many interactions involving N should occur in 1966 (see Tables 7-3, 7-4 and 7-5). Prior to 1966 the influence of K on wood properties was not dependent on the level of N. In 1966 the effect of K on mean density, minimum density, LW 35 and LW 45 was influenced by the availability of N.

It is suggested these interactions were associated with the very dry spring of 1966 (see also Chapter 6). It is known (Kramer and Kozlowski, 1960) that P and K are very mobile within trees but N is very much less mobile. If the tree is more dependent on current uptake by the roots for its requirements of N, then moisture deficits during the period of greatest nutrient demand might well produce a temporary deficiency of N where it has not been added as fertiliser. The lack of an NK interaction in 1964 and 1965 indicates sufficient N was available to the tree from natural sources in those years to meet the increased requirements due to the addition of K. Spring rainfall in those seasons was much higher than in 1966.

Support for this hypothesis is provided by the observation of Hall and Raupach (1963) that the effect of potassium deficiency on P. radiata in the adjacent KCl experiment was more prominent in spring than at other times of the year. These workers also reported an apparent recycling pattern with K and P, but not with N.

An examination of the data presented in Table 7-1 shows that the parameter mean latewood percentage appears better able to describe changes in the densitometric curves than mean density. For example, mean density did not indicate a large effect of N on the 1963 density curve, but the effect was well brought out by mean latewood percentage. In subsequent years both parameters followed a very similar trend.

This experiment has yielded some important results. Certain fertilisers have been shown to influence wood density in specific directions not necessarily associated with an influence on growth rate. Very high levels of nitrogen depressed density maxima but maxima were increased by high levels of superphosphate. Nitrogen was effective in the season of application whereas the effect of potassium and superphosphate was not evident until the following season. Potassium was associated with large reductions in mean density, minimum density and mean latewood percentage and was still strongly affecting these parameters four years after application.

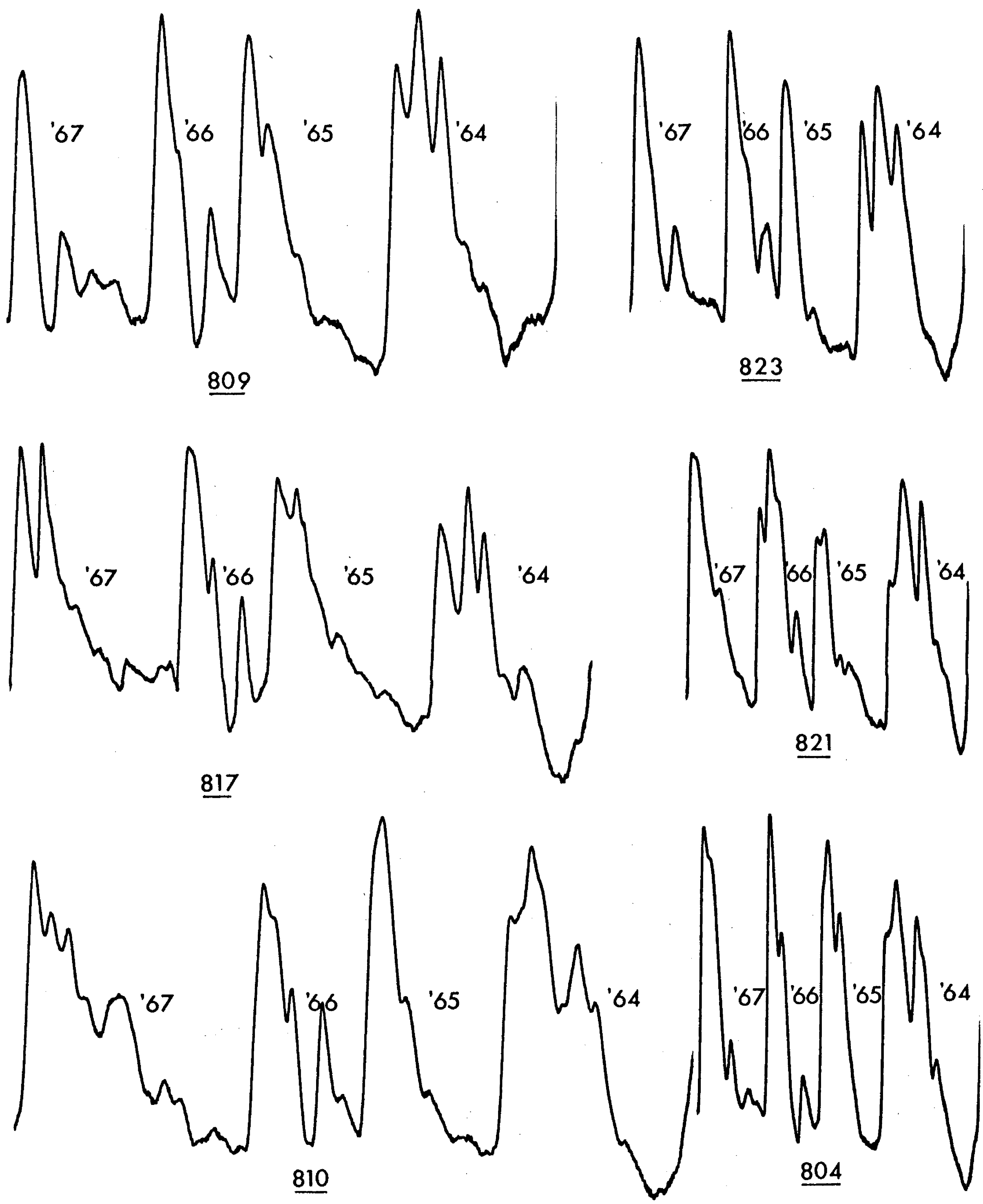
Fertilisers and "False Rings".

The addition of fertilisers accentuates the patterns of density variation within the ring and leads to the development of more prominent "false rings". This trend is shown very clearly in Figure 7-1, which presents density tracings for the last four rings for three trees chosen at random from each of the NPK and control treatments.

In the 1964 ring the tendency toward three peaks in the latewood band was more strongly developed in the fertilised trees. Despite a wider latewood zone, mean density was lower in the three NPK trees because they had much more low density earlywood than the control trees. Similarly, the 1965 rings show the fertilised trees were more sensitive to variations in growing conditions.

Every tree from Flynn Creek Tree Farm examined in this study had a "false ring" in 1966. In the unfertilised trees this subsidiary density peak was quite small, but

FIG. 7-1 Density tracings of fertilised trees (809, 817, 810) and trees not fertilised (823, 821, 804).



in the fertilised trees it was very prominent. Possibly the greater number of "false rings" reported by Ishikawa and Kuroyanagi (1963) for fertilised sugi (Cryptomeria japonica) was due to their being more easily seen, rather than more prevalent.

The 1966 thinning had a considerable affect on wood formation in the 1967 ring. Although spring rainfall was below that of 1966, earlywood development was much greater in all trees, and especially in the fertilised trees. Again the fertilised trees exhibited more minor variations in density. After thinning there was a general trend for the density curves to be less similar between trees, perhaps reflecting greater variation in individual growing space.

The density tracings in Fig. 7-1 clearly demonstrate the greater within-ring density range in the fertilised trees.

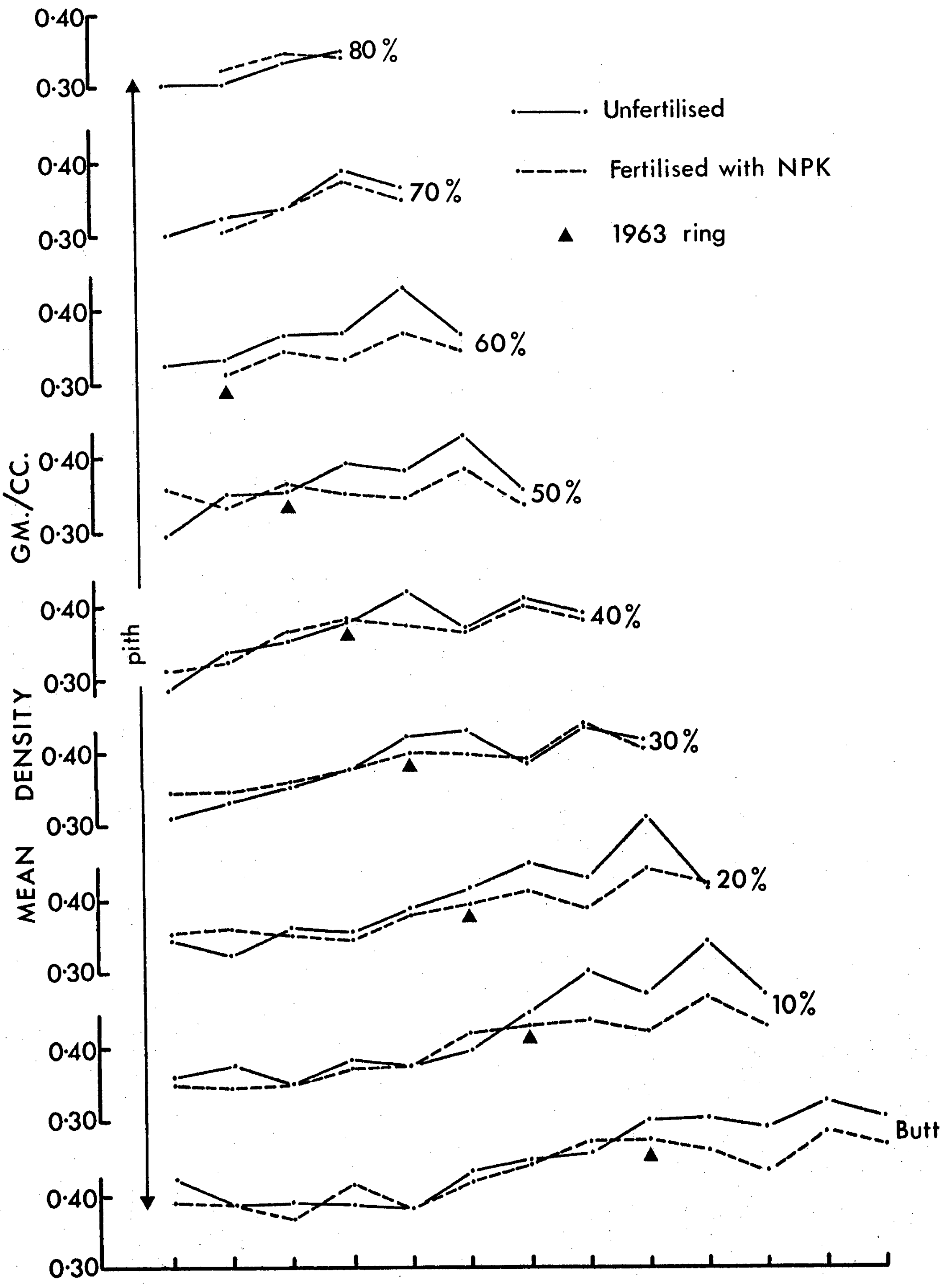
7.3 Results and Discussion : The Within-Tree Study.

Variation in Density Within the Tree.

Wellwood, Ifju and Wilson (1965) reported that nitrogen fertiliser had produced a greater reduction in wood density in the lower bole of western red cedar (*Thuja plicata*) than at higher levels. The addition of NPK fertiliser to *P. radiata* at Flynn Creek was associated with a similar response for mean density and minimum density.

Average data for mean, minimum and maximum density for each ring at every sampling height were calculated for the nine fertilised and nine unfertilised trees. In respect of mean density (Fig. 7-2) the two groups were

FIG. 7-2 Variation in mean density from pith to bark with percentile height in tree (average of 9 trees).



very similar in the lower bole up to 1962; in 1963 density of fertilised trees was less than unfertilised trees, and the difference increased over the next three years, consistent with the results presented in the previous section.

From 30 percent of tree height upwards there was little difference between the two groups except at the 50 and 60 percent levels. However, the lower density in the NPK trees at 60 percent was an artifact due to the differing physiological age of the material in the two groups at that height. From the 60 percent level upwards there was one ring less in the fertilised trees, hence the same ring, at the same percentile height, was physiologically one year younger in these trees (Richardson 1961) and therefore of lower density. If density at the 80 percent level in the control trees is compared with density at the 70 percent level in the NPK trees (both having four rings) it is seen that the fertiliser produced a small increase in density high in the trees. The difference in density between the two groups of trees at 50 percent of tree height is also due to variation in ring numbers, there being only four of the nine fertilised trees with seven rings at that height.

Thus, sampling for the within-tree study was not completely satisfactory. The results emphasise the need in studies of this nature to sample at equivalent growth stages from the apex, as advocated by Richardson (loc. cit.). Sampling at fixed percentage intervals assumes that all trees followed the same course of growth. This cannot be so if the fertiliser treatments were applied when the trees were already of considerable size, as they were in this study.

The variation of minimum density within the tree followed a pattern similar to mean density (Fig. 7-3).

Maximum density in the lower bole was depressed in 1963 by the N component of the fertiliser (see the previous section) but the effect extended only as far as 20 percent of tree height (Fig. 7-4). In 1964 and 1965 maximum density was higher in the fertilised trees but fell to about the same level as the unfertilised trees in 1966 and 1967, reflecting the influence of the P in the fertiliser.

The increase in maxima in 1964 and 1965 due to NPK appeared to be greater above 50 percent of tree height than in the lower bole, if allowance is made for the sampling errors discussed above. Moreover, in the upper bole the differences between maxima for fertilised and unfertilised trees were maintained in 1966 and 1967.

Thus there are two different trends in the influence of NPK - an increasing effect with increasing height in tree for maximum density, but a decreasing effect with increasing height in the tree for mean and minimum density.

The Breast Height - Whole Tree Density Relationship.

It is to be expected the changes in distribution of density within the tree associated with fertilisation will be reflected in a changed relationship between breast height and whole tree density values. There is, in fact, a very marked change. The regressions for the two groups of trees and the data contributing to them are presented in Fig. 7-5, the X-ordinate being weighted average density at breast height and the Y-ordinate being weighted whole tree density to a three-inch top diameter limit. Analysis of the regressions established that they do not differ in

FIG. 7-3 Variation in minimum density from pith to bark with percentile height in tree (average of 9 trees).

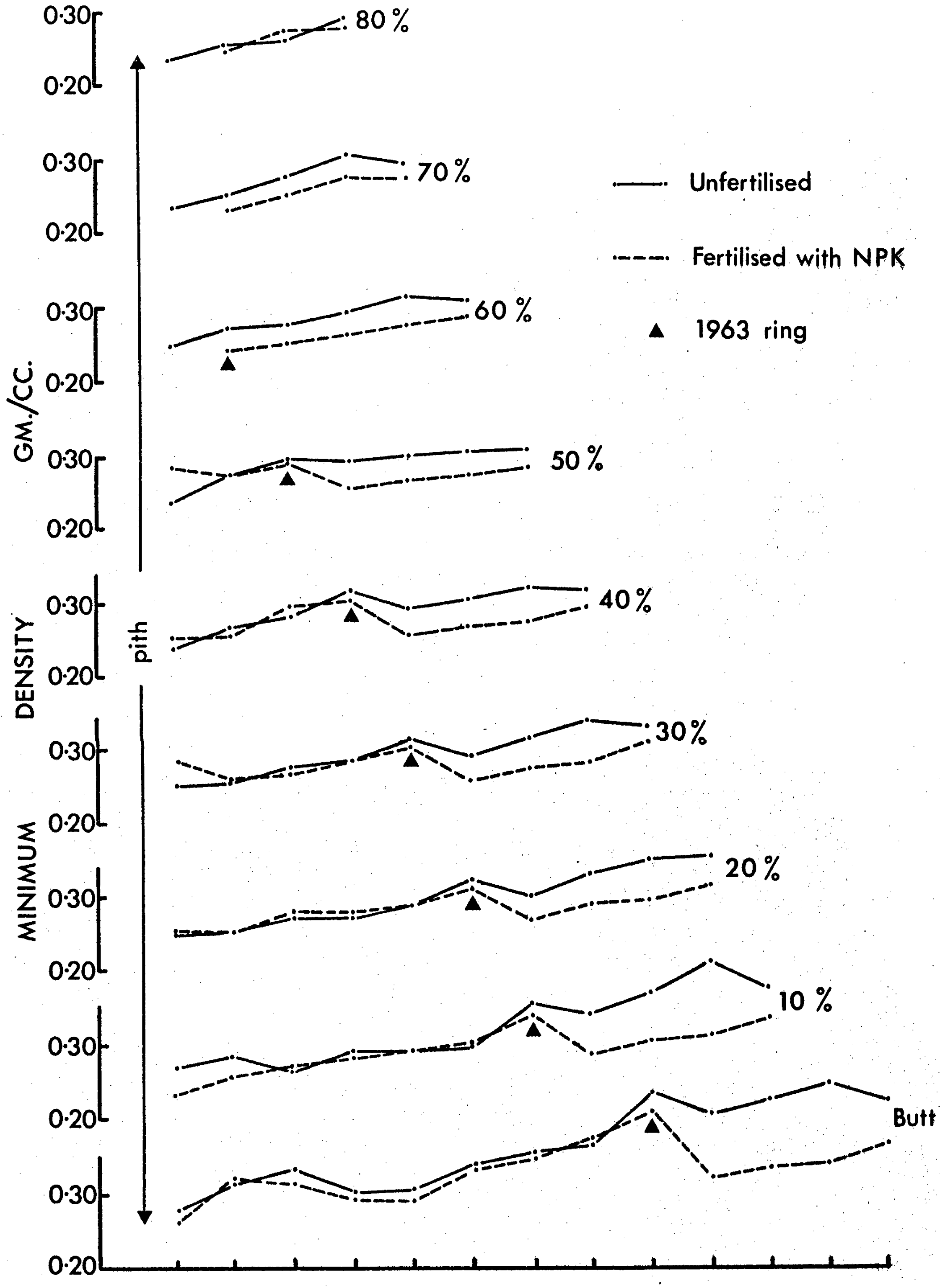


FIG. 7-4 Variation in maximum density from pith to bark with percentile height in tree (average of 9 trees).

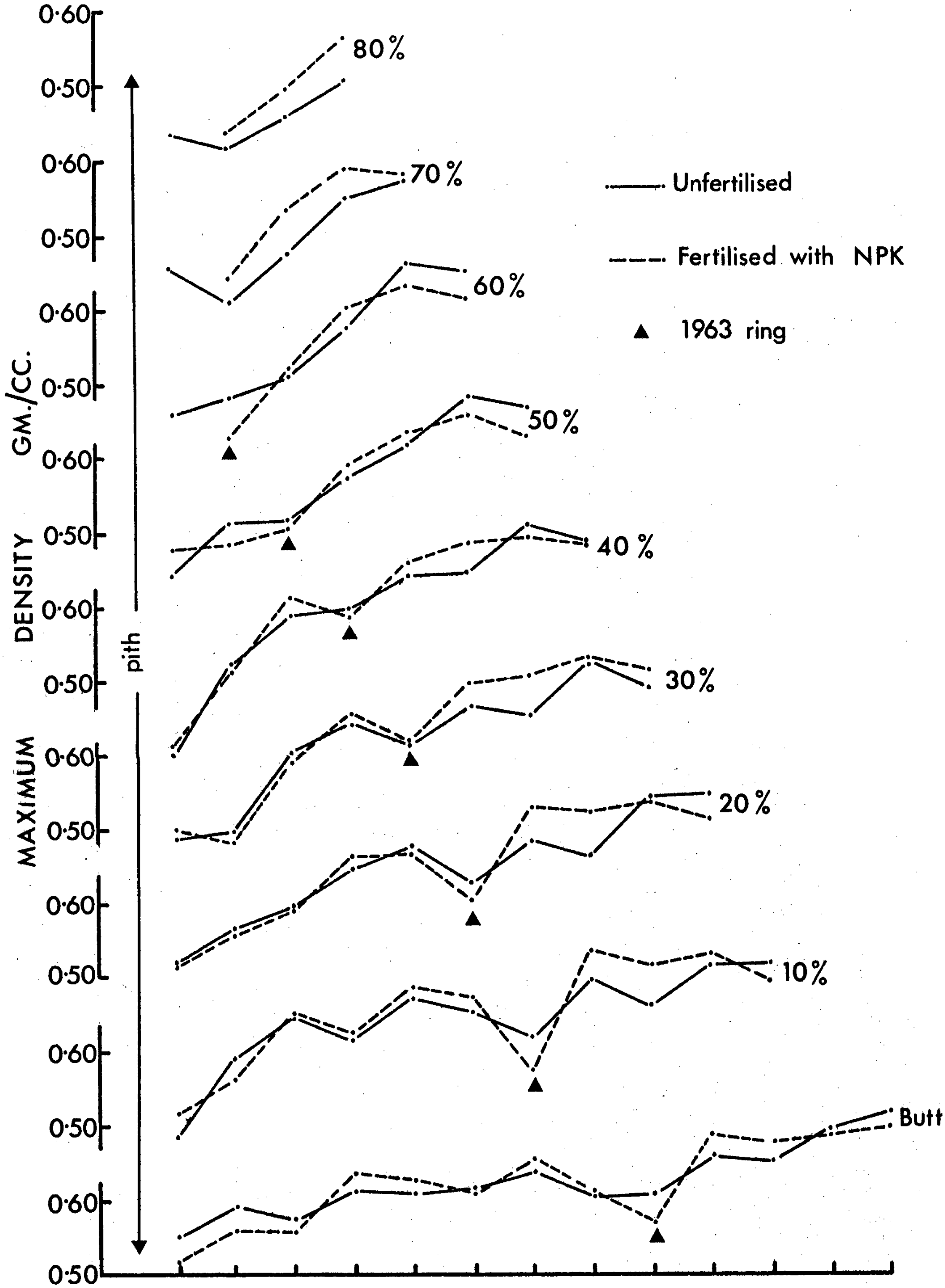
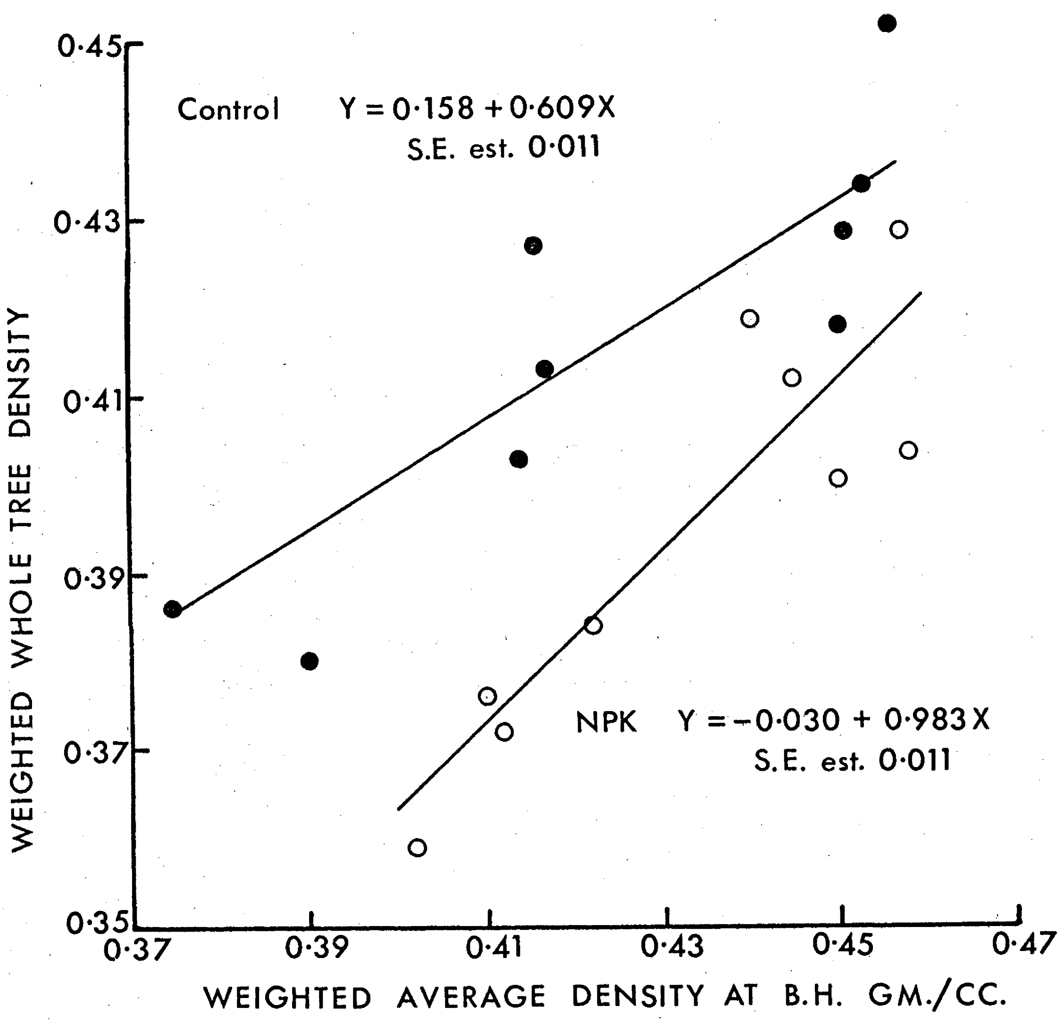


FIG. 7-5 Effect of NPK fertiliser on the breast height - whole tree density relationship.



slope but they are significantly different in level, the variance ratio being 24.06 for 15 degrees of freedom.

These results are of considerable importance for the evaluation of the influence of fertiliser on wood properties. The regressions in Fig. 7-5 indicate that, under the conditions described in this study, a tree with a weighted average density at breast height of 0.430 would have a whole tree density of 0.392 if fertilised with NPK, but a whole tree density of 0.420 if unfertilised.

Hence, a comparison of the effects of fertiliser at breast height only will underestimate the total effect of the fertiliser. Precise definition of the effect of fertiliser on wood properties, therefore, requires investigation of both the within-tree and between-tree variation.

Earlywood and Latewood Growth.

The reductions in mean density by fertiliser have been achieved mainly by an increase in earlywood production. Whereas breast height data provides a useful indication of earlywood growth (as, for example, in the KCl experiment, p. 93), definitive results are provided only by whole tree data. The volume of earlywood and latewood in each sheath from 1962 to 1967 was calculated for all 18 trees on the computer program VOLS (see Appendix I). The boundary between earlywood and latewood was a density level of 0.468.

Average earlywood, latewood and total sheath volume for each increment are shown in Table 7-6.

TABLE 7-6 Average earlywood, latewood and total volume for each sheath from 1962 to 1967 (cu. ft.) to a three-inch top.

		1962	1963	1964	1965	1966	1967
Earlywood Vol./Tree	NPK	0.275	0.270	0.514	0.583	0.477	0.974
	Cont.	0.244	0.243	0.195	0.230	0.206	0.383
Latewood Vol./Tree	NPK	0.053	0.059	0.158	0.147	0.173	0.232
	Cont.	0.034	0.057	0.075	0.061	0.094	0.122
Sheath Vol./Tree	NPK	0.328	0.329	0.672	0.730	0.650	1.206
	Cont.	0.278	0.300	0.270	0.291	0.300	0.505

Before fertilisation, earlywood and latewood production were comparable in both groups of trees, but in each season from 1964 to 1967 the fertilised trees produced about 150 percent more earlywood and about 110 percent more latewood volume.

The year-to-year trends in earlywood and latewood production from 1962 to 1966 were directly related to rainfall in the appropriate part of the growing season. In 1967 the relationship did not apply as the existing balance of conditions had been completely altered by the thinning late in the 1966 season.

The total sheath volume data emphasise the speed and magnitude of the response to fertiliser in this experiment. In the first season following treatment, average volume growth in the fertilised trees was more than double that in the unfertilised trees, and this difference was maintained throughout the period of study.

Individual Tree Response to Fertiliser.

Posey (1964) concluded that loblolly pine trees with an initially higher wood density exhibit a greater fall in density after fertilisation. It has been shown in the present study (Chapter 6) how fertilisation does not influence *P. radiata* in this way. In fact, the reverse may be true.

The significance of any possible individual tree response to fertiliser can properly be evaluated only on whole tree values because of the tendency for changes in wood density due to fertiliser to be greater in the lower boles of trees.

The whole tree density of the nine NPK-treated trees before fertilisation was compared with the average density of the wood produced after fertilisation. The latter was calculated as follows:

$$\text{average density} = \frac{(\text{Dry weight increment 1963-1967})}{(\text{Volume increment 1963-1967}) \times 62.5}$$

The relevant data for each tree are given in Table 7-7.

TABLE 7-7 Individual tree increment and density data NPK trees

Tree No.	Volume Inc. 1963-1967 (cu. ft.)	Dry Wt.Inc. 1963-1967 (lb.)	Average Density 1963-1967	Whole Tree Density 1962
4	2.27(a)	58.6(a)	0.413(b)	0.410(b)
5	3.16	80.0	0.405	0.390
6	3.24	73.4	0.364	0.349
7	4.34	118.3	0.437	0.407
8	5.11	120.7	0.376	0.368
9	3.53	88.3	0.400	0.403
13	2.68	64.6	0.383	0.379
14	2.78	64.8	0.373	0.365
15	3.89	102.0	0.420	0.410

Note: (a) Volume and dry weight both at 8 percent moisture content.

(b) In gm./cc.

The linear regression of average density of the wood produced after fertilisation on whole tree density before fertilisation was $Y = 0.011 + 0.996X$, with a correlation coefficient of 0.922. The value of the regression coefficient, almost unity, shows the influence of initial whole tree density was negligible. Whereas there may be a negative relationship between initial wood density and response to fertilisation in the lower bole, the effect is insignificant on a whole tree basis. From the practical aspect, therefore, it can be ignored.

<u>Tree Taper and Wood Density</u>.

Tree stem form is strongly influenced by the quality as well as the quantity of wood produced. It has been demonstrated (Trendelenberg, 1932, 1935, Schniewind, 1962) that a tree can be strengthened by a larger volume of low density wood or a smaller volume of high density wood. According to Volkert (1941) stem form and wood density are intimately related and the factors which affect stem taper can also be used to explain many of the patterns of variability of wood density.

The conclusions of these workers are supported by the present study. The greater effect of fertiliser in the lower bole of the NPK trees was accompanied by a greater radial growth in the lower portions of the bole, with a consequent increase in stem taper. After first checking that stem taper in 1962 was the same in the two groups of trees used for the within-tree study, the group linear regressions of sectional area in 1967 on percentile height in the tree were calculated. The two regression equations were:

for the fertilised trees $Y = 0.373 - 0.004H$ (correlation coefficient 0.936)

and for the unfertilised trees $Y = 0.263 - 0.003H$ (correlation coefficient 0.939)

where Y was sectional area in square feet and H was the percentile sampling height, excluding the butt data, which is affected by butt swell.

Analysis of the regressions established that they differ significantly in slope, the variance ratio being 23.89 for 136 degrees of freedom.

Pegg (1966) reported a significant increase in Girard form class, that is, decreased stem taper, after application of nitrogen fertiliser to a 23-year old stand of loblolly pine.

He hypothesised from this that density had been reduced more at higher levels in the tree by the fertiliser treatment than at breast height. Such a result is completely the reverse of the pattern of response to fertiliser found in the present study and also that of Wellwood, Ifju and Wilson (1965).

Pegg's results may have been influenced by the imprecise nature of Girard form class as a measure of stem form, but it is more likely they are due to the growing conditions associated with very high levels of stocking on his experimental area. Stocking ranged from 1800 to 2100 stems per acre at the time of fertilisation to 1200 to 1700 stems per acre at the time of measurement at age 23. With such intense competition between trees (the changes in stocking were due entirely to deaths from suppression) increment would always be concentrated in the upper parts of the bole, therefore any stimulant to growth which did not change these conditions would lead to decrease in stem taper.

Stocking levels in planted stands of *P. radiata* in Australia are rarely higher than those in the stand used in the present study, therefore an increase in stem taper will be the usual result of fertilisation in this species. This fact should be taken into account in the evaluation of volume responses to fertiliser treatment. Errors in tree volume measurement may be involved unless volume is determined from a three-way tree volume table which includes a measure of stem taper.

CHAPTER 8

FERTILISER AND WOOD PROPERTIES (IV)

The Belanglo "Super Trial"

8.1 Experimental Material and Methods.

The Fertiliser Experiment.

The oldest fertiliser experiment used in this study was established at Belanglo State Forest by the N.S.W. Forestry Commission in spring 1951, using five levels of superphosphate - 0, 2, 4, 6 and 8 cwt. per acre. There were three replicates of each treatment in a randomised block design. The stand had been naturally regenerated so that tree age when sampled for this study varied from 18 to 22 years. The experiment was thinned for the first time in August, 1967, immediately prior to the collection of the wood samples so that all samples came from the remaining trees which were dominants or codominants. Only the 0, 4 and 8 cwt./acre treatments were sampled.

Stand details presented in Table 8-1 indicate the response to the fertiliser additions.

TABLE 8-1 Growth responses to 1967

Fertiliser Level cwt./ac.	Predominant Height ft.	Basal Area ft.^{2}/ac.	Merchantable Volume (Total) cu. ft./ac.
0	44	44	633
4	63	121	2418
8	62	144	2879

Mean annual ring widths for the 27 sample trees (Figure 8-1) indicate there was a greater initial response to 4 cwt. of superphosphate but that from 1958 onward the 8 cwt. per acre treatment produced the largest increment. The greater initial response in the 4 cwt. plots may possibly be due to their lower stocking (Table 8-2).

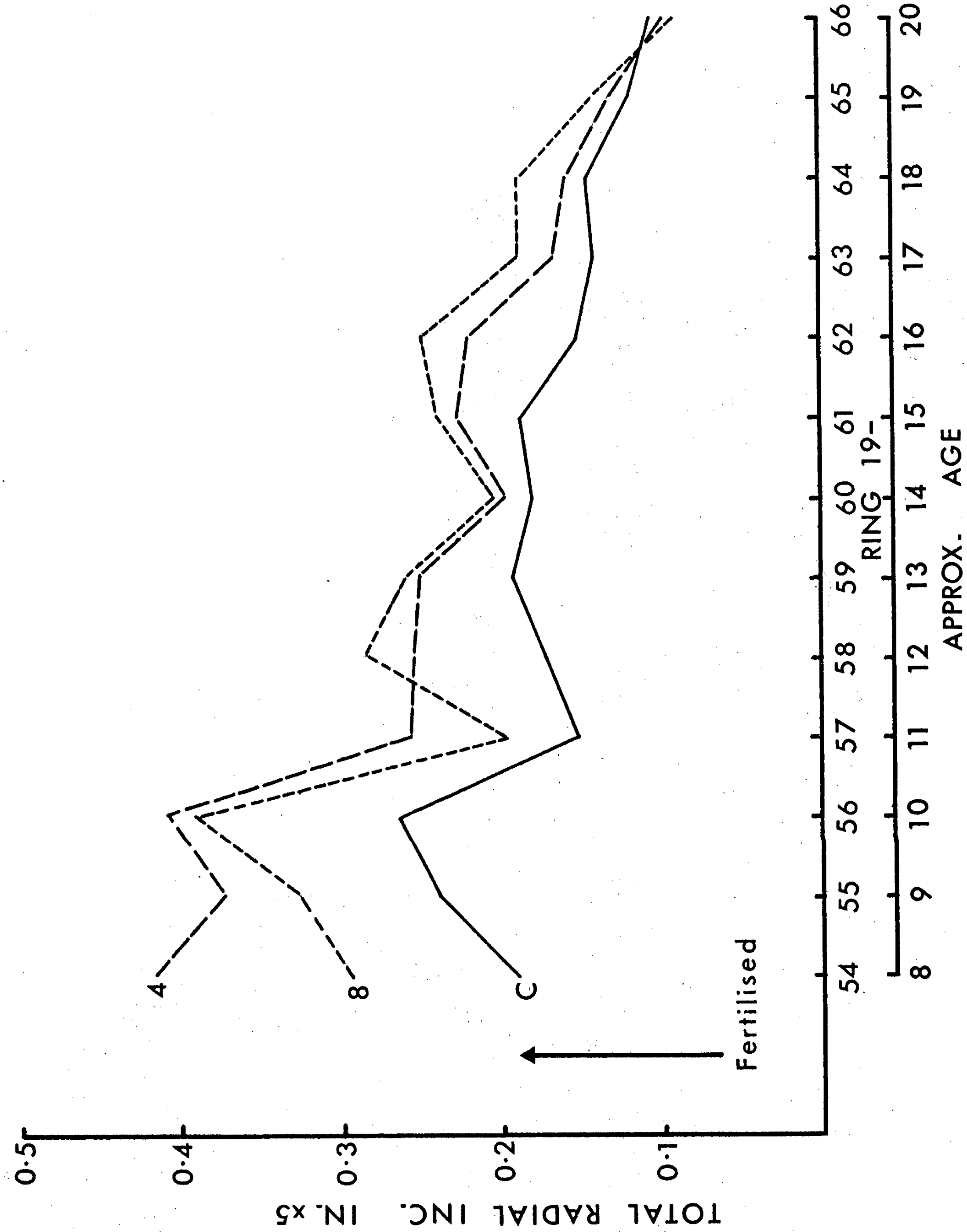
TABLE 8-2 Stocking per acre 1952 - 1967

Fertiliser Level cwt./ac.	Block			Mean
	I	II	III	
0	263	158	140	187
4	333	246	333	304
8	386	579	298	421

Sampling.

Three trees from each replicate plot were sampled with the Solo chainsaw tree sampler - a total of nine trees per treatment and 27 trees in all. Most sample trees came from the measured plots but some came from the plot surrounds, which had received the same treatment. The latter trees

FIG. 8-1 Average radial increment.



were obtained as close as possible to the measured plot boundary. One sample block was collected from each standing tree from bark to pith at about breast height on the northern side of the stem.

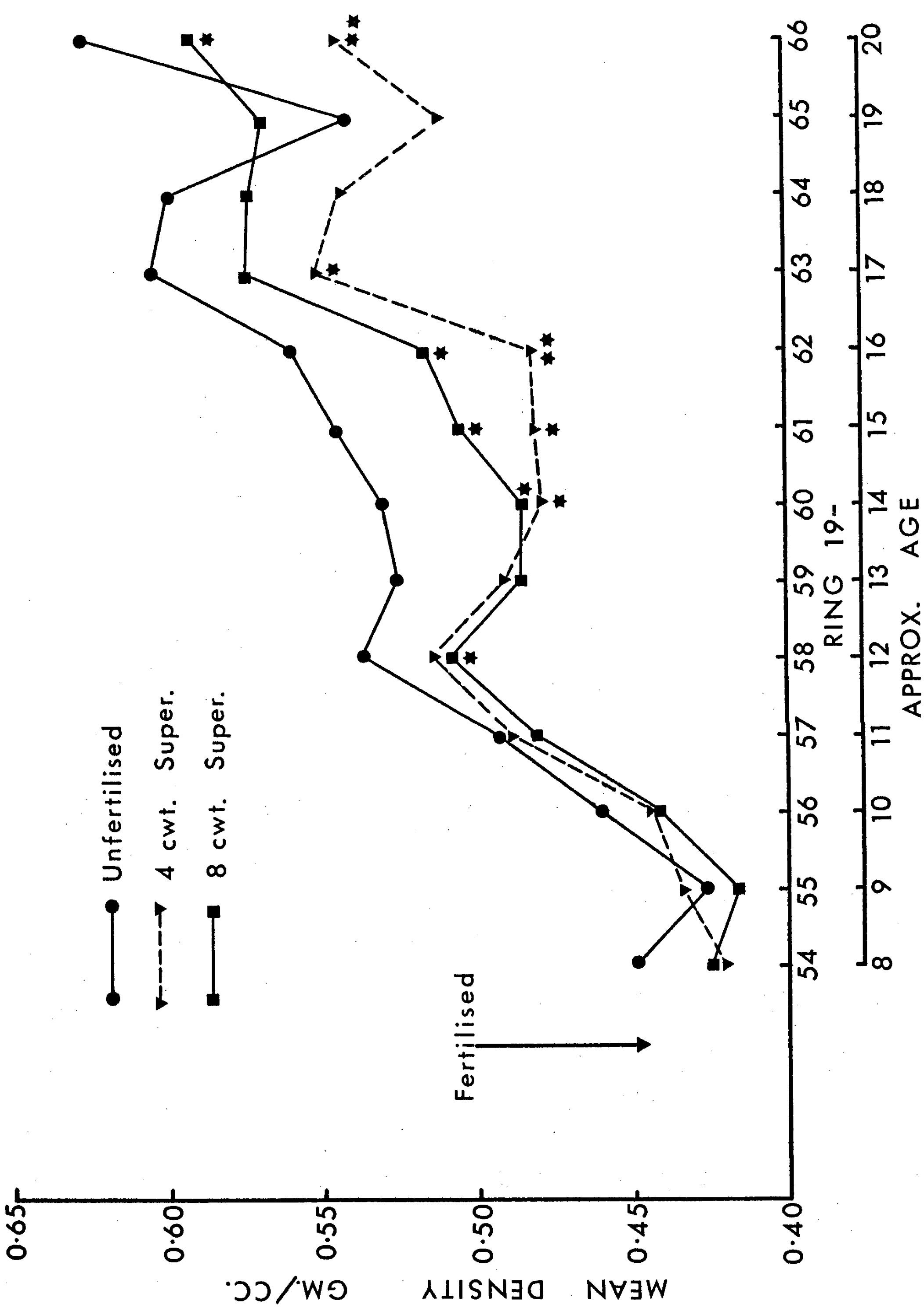
The samples were prepared for X-radiography and measurements obtained using the standard procedures detailed earlier (p. 24). The data were subjected to a randomised block analysis by annual rings and also on averages over the period 1954 to 1966. No measurements could be made in earlier years since several trees contained no rings prior to 1954 at the point of sampling. The latewood percentage data were converted to arcsin values for analysis.

8.2 Results.

The effect of the fertiliser treatments on ring mean density for each year is shown in Figure 8-2. There is a clear trend for the addition of fertiliser to be accompanied by a reduction in wood density. The treatment means for both levels of superphosphate were less than the mean for the unfertilised control in almost every year, but the differences were statistically significant in only six of the 13 years. For the period 1954 - 1966 the unweighted average density for both fertiliser levels was significantly less than the control at the one percent level, the treatment means being 0.530, 0.491 and 0.506 for the 0, 4 and 8 cwt. treatments respectively.

In each year from 1954 to 1959 the mean density for the 4 cwt. treatment was higher than for the 8 cwt.

FIG. 8-2 Effect of superphosphate on mean density.



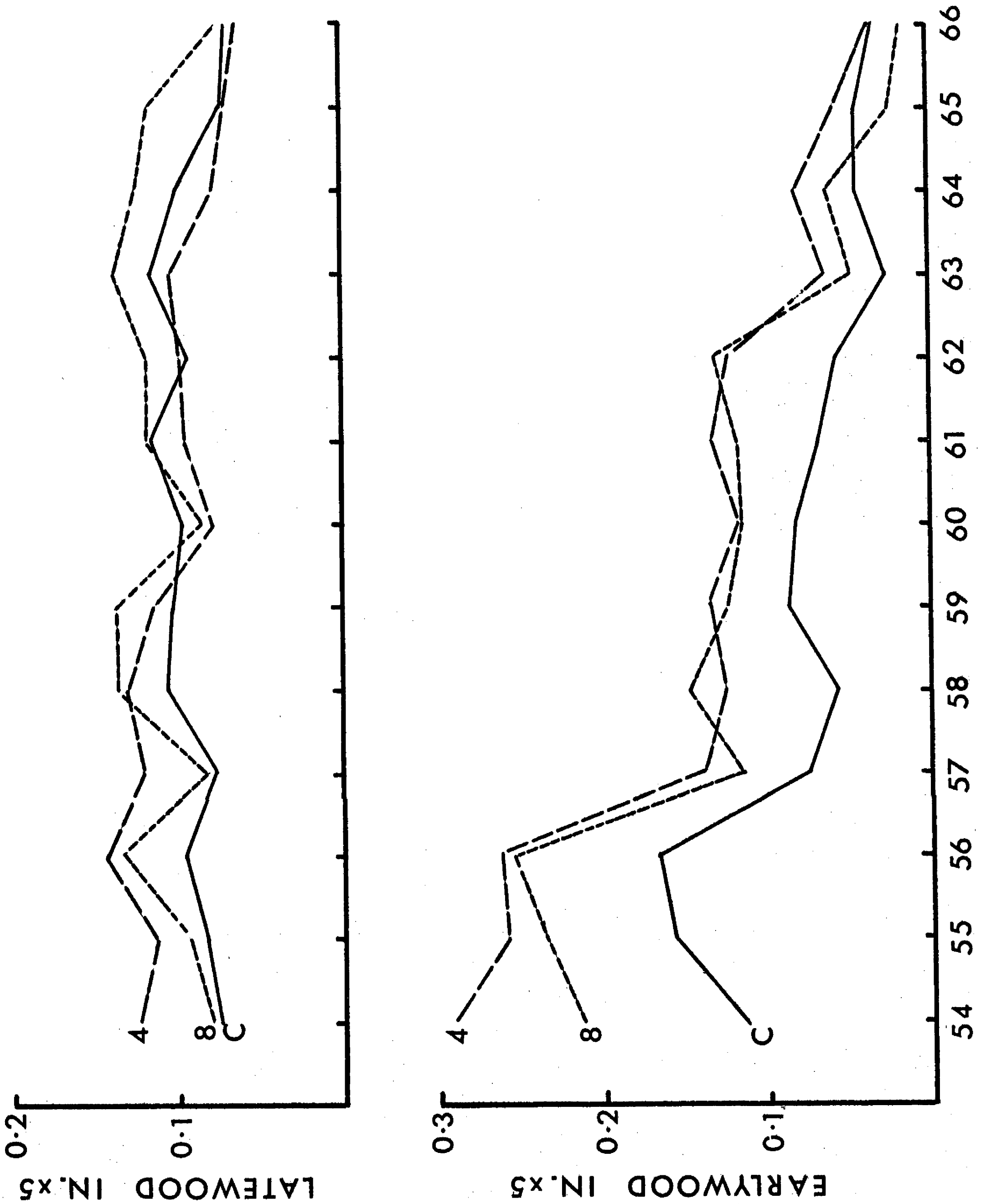
treatment, but thereafter the latter treatment resulted in a higher wood density, a tendency which was accentuated with time. The mechanism for this rather unexpected result can be seen in the patterns of earlywood and latewood increment (Figure 8-3). From 1958 onward earlywood increment in the 4 cwt. treatment was at a similar or slightly higher level than in the 8 cwt. treatment. However, latewood increment over the same period was consistently less (by as much as 58 percent in 1964), consequently mean ring density had to be less.

The inability of the 4 cwt. trees to grow as much in the latewood phase was probably due to a less well developed root system, resulting in an inability to exploit soil moisture fully during periods of water stress. This explanation is supported by the results of Gentle, Humphreys and Lambert (1965) who worked with a similar stand at a plantation close to Belanglo. They found that root development in a rock phosphate treatment, which is a slowly available source of P, was not as good as that under 8 cwt. of superphosphate, while root development on unfertilised plots was extremely poor.

The optimum level of superphosphate application at Belanglo is at least 6 cwt. per acre (Gentle and Humphreys, 1967) due to the high degree of immobilisation of P by the soil. Trees fertilised with less than 6 cwt. are more affected by drought. In 1967/68 this area received its worst drought on record and dead needles resulted over most of the crown surface in the 0, 2 and 4 cwt. treatments, whereas the 6 and 8 cwt. treatments were much less affected (Gentle, pers. comm. 1969).

The data for latewood percentage at the four levels of density 0.35, 0.45, 0.55 and 0.65 as well as mean latewood percentage (MLW), are given in Table 8-3. These

FIG. 8-3 Average radial increment for early- and latewood.



data generally support the mean density results. The greatest differences in latewood percentage occurred for LW 45 and LW 55. In the fertilised trees density rose more rapidly into the high density zone, that is, the transition from earlywood to latewood was affected by the superphosphate.

TABLE 8-3 Latewood percentage data - Belanglo "Super Trial"

TRT	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
	MLW												
0	33.9	30.3	41.0	52.6	64.1	64.4	64.8	67.1	70.3	82.7	77.7	69.9	78.0
4	24.9*	30.3	36.0	52.3	56.8*	52.3	45.8**	46.7*	46.2**	68.9*	62.1*	60.7	65.1
8	20.8*	28.6	37.6	50.2	54.9**	53.3	49.6**	56.4	57.0*	75.3	73.3	79.2	80.5
	LW65												
0	1.7	3.9	10.6	6.9	18.5	21.0	23.8	22.8	27.2	35.2	40.1	26.8	42.0
4	5.1	7.9	11.9	19.0**	16.7	17.7	20.2	15.4	17.3*	25.0*	27.9	16.0	17.3**
8	3.2	5.5	11.1	10.3	19.4	13.4	21.6	18.7	20.3	25.0*	33.7	28.4	32.2
	LW55												
0	16.4	13.8	21.9	32.7	42.3	37.1	41.6	38.4	48.2	64.4	56.3	47.0	59.4
4	10.5	13.5	18.4	33.2	31.3*	29.2	31.3**	27.3*	26.5**	44.6*	35.4*	33.9	35.0*
8	10.1	13.3	20.0	27.8	27.9*	23.2*	29.5**	30.8*	30.8*	53.5	44.9	50.7	60.7
	LW45												
0	40.1	31.7	35.4	61.2	77.1	65.0	67.3	79.7	78.5	98.0	87.6	78.4	85.1
4	24.7*	25.3	33.4	53.1	60.7*	51.8	41.7*	44.6*	47.6*	79.1	57.8**	68.0	81.3
8	20.6**	22.9	32.2	43.9	54.9*	62.6	46.2*	58.3	55.6*	92.3	85.6	98.8	96.7
	LW35												
0	90.1	83.3	94.0	99.5	99.3	99.8	100	100	100	100	100	100	100
4	71.6	82.8	84.3*	95.2	99.5	97.9	87.8**	94.1	90.3	100	100	100	100
8	63.1*	83.3	88.9	99.9	99.4	99.2	93.9**	99.4	99.7	100	100	100	100

Maximum density was consistently higher in the fertilised trees except in 1965 and 1966, although the differences from the control were statistically significant in only two years (Fig. 8-4a). Average maxima for the 4 cwt. treatment were higher than those for the 8 cwt. treatment up until 1960. Thereafter they tended to be very similar or slightly below the latter.

The increase in maxima by the P fertiliser is in agreement with the results previously presented (Chapter 5 and Chapter 7). The higher maxima associated with the 4 cwt. treatment are difficult to explain, but may be a reflection of differences in competition caused by the variation in average stocking between treatments (Table 8-2).

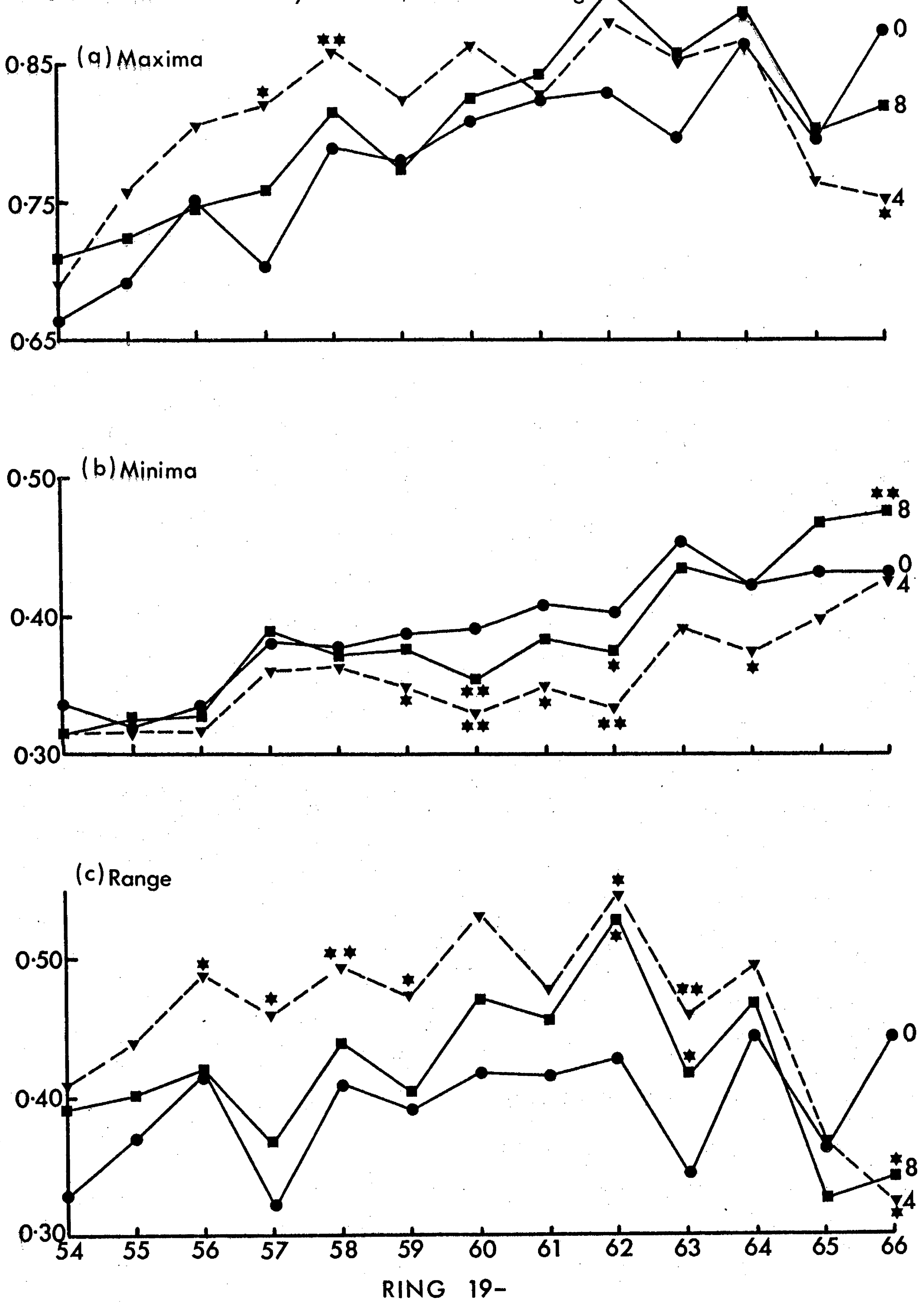
There was a general tendency for minimum density to be lower in the fertilised trees, as in the other fertiliser experiments, although the differences were significant in only six of the 13 years and were greater in the 4 cwt. treatment.

Due to the reduction in minimum ring density and increase in maximum ring density, the density range was increased by superphosphate. The increase was statistically significant in seven individual years for both fertiliser treatments but overall for the 4 cwt. treatment only.

8.3 Discussion.

Although the data presented here are generally consistent in their pattern, there is an anomalous variation in 1965. In that season, mean density, latewood percent at 0.45 and maximum density all deviated from the previous trends. Two factors contributed to this.

FIG. 8-4 Trends in density maxima, minima and range.



Firstly, poor late spring rainfall curtailed earlywood development, the trees receiving 8 cwt. of superphosphate being most affected and the controls the least. Over the period 1963-1966 radial earlywood increment was always less in the 8 cwt. than in the 4 cwt. plots and in 1965 and 1966 less even than the controls. Taking into account the age of the trees and the plot stocking (Table 8-2) this is almost certainly due to restriction of increment by overstocking. Secondly, this season had the lowest January - May rainfall of the 13 years from 1954 to 1966. Probably little or no growth took place in the latter part of this period so that maximum latewood density did not rise as high as it did in previous years of lower water stress.

As an experiment the "Super Trial" has a number of deficiencies. It is not an even aged stand as it regenerated naturally over a number of years following an earlier crop and it is likely the trees were very unthrifty at the time the fertiliser was applied. The breast height sampling point is not entirely representative because of the considerable differences in height between treatments (Table 8-1). The effect is to give an upwards bias to the density estimates on the fertilised plots. In spite of the differences in height, however, the average number of rings at breast height was virtually the same in all treatments.

The plots were completely untended from 1952 to 1967 and there was severe scrub growth in the control plots but not in the 4 cwt. and 8 cwt. plots.

The considerable variation in plot stocking both within and between treatments undoubtedly influenced tree growth, and hence wood properties, in the latter part of the study period. It is impossible to estimate how much influence the stocking may have had in the early part of the study period. It is likely this was responsible for the variable, but generally large, block effect in the analysis of variance for all parameters.

The effect of rock phosphate and superphosphate on the wood density of P. radiata at Penrose Forest, a few miles from Belanglo, was examined by Gentle, Bamber and Humphreys (1968). Basic density was determined for every second ring from the pith to ring 14 on discs removed from the top of one randomly selected butt log in each of five replicate blocks of the three treatments. From this rather small sample they concluded the basic density of the control trees was not different from basic density of trees in either fertiliser treatment, but the basic density of trees treated with superphosphate was significantly higher than for trees treated with rock phosphate. Since the quantity of P available to the trees was very much less under rock phosphate, the results are very similar to those of the present study.

The small sample used in the Penrose work raises the question of whether the sample size at Belanglo, chosen on the basis of limited previous experience, was adequate. This can be checked by use of the following formula:

$$n = \frac{2\ t^2\ s^2}{D^2}$$

where t = "t" value for 2n-1 degrees of freedom

s^2 = variance among tree means

D = difference between means which it is desired to detect, set at 0.030 gm./cc. in this case.

Variances for the 1954/1966 tree means were 0.000872, 0.001046 and 0.000727 for the 0, 4 and 8 cwt. treatments respectively. Fitting these figures into the above equation, we have:

$$\text{Control} \quad n = \frac{2\ (2.11)^2 \times 0.000872}{(0.03)^2} = 8.6$$

$$\text{4 cwt.} \quad n = \frac{2\ (2.11)^2 \times 0.001046}{(0.03)^2} = 10.4$$

$$\text{8 cwt.} \quad n = \frac{2\ (2.11)^2 \times 0.000727}{(0.03)^2} = 7.2$$

That is, from 7 to 10 trees would be required to detect a difference between treatments of 0.030 at the 95 percent half confidence limit. If the difference required is set at 0.020 instead of 0.030 the corresponding figures are 16 to 23. Thus, in retrospect, it can be seen how the sample size of nine trees per treatment was barely adequate to show that the differences found were real.

Sample size calculations for individual ring density values are not so clear. Within any treatment the variance for mean density varies widely from year to year, with a tendency to increase with increasing tree age, a reflection of environmental factors and increasing within-stand competition, as found also in the Flynn Creek KCl study (Chapter 6). The variance figures are generally, but not always, higher than those quoted above, with consequent effects on the estimate of required sample size. The analyses for individual years can therefore be accepted with less confidence than the analyses based on overall data.

The effect of fertiliser application on wood properties is seen then to depend on the particular combination of site, seasonal growing conditions, stand age and stand condition. If, for example, the natural level of fertility of the Belanglo site had been that of the 4 cwt. plots, the addition of superphosphate would result, not only in an increase in volume yield, but also in an increase in wood density since the stimulation of the root system by the fertiliser would have enabled more latewood growth.

Another interesting aspect of these results is the duration of the fertiliser effect on wood quality. In spite of a marked falling-off in radial increment (relative to the controls) at both levels of superphosphate in the latter years of the study period there was no tendency for a narrowing of differences in wood density, apart from 1965, when anomalous seasonal conditions exerted an overriding influence.

CHAPTER 9

EFFECT OF SOIL WATER AVAILABILITY ON WOOD DENSITY

9.1 Introduction.

The pattern of within-ring variation in wood density in any growing season is similar from tree to tree, as noted previously in this study (Chapters 2 and 7) and by Polge (1965b). The most variable factor of the environment and the one most likely to be responsible for these characteristic patterns is moisture availability (Zahner, 1963). The continuous curves of wood density variation provided by the technique used in the present study enable a quantitative examination of the influence of the soil moisture factor on wood properties.

An investigation of the covariation of water availability and wood density requires estimates of the former at close intervals throughout the growing season. Zahner and Stage (1966) calculated water deficits on a daily basis as the difference between the amount of water actually supplied to the trees from the soil and the amount which could be utilised by the trees under existing weather conditions. Buckingham and Woods (1969), employed a simulation model to relate volume growth of loblolly pine to soil moisture deficit. The model estimated soil moisture content on a daily basis by subtracting the amount lost by evapotranspiration from the soil moisture content of the previous day and then adding the amount of rainfall since the previous day. Moisture deficit was assumed to be the amount by which the computed soil moisture content fell below the soil moisture holding capacity. Moisture was removed from the soil in layers successively downward and potential evapotranspiration (PE) was determined by the method of Thornthwaite and Mather (1955). Daily evapotranspiration was calculated from the PE by correcting for soil moisture content using the relationship

$$E = \frac{M}{S} (PE)$$

where M represented soil moisture content of the top layer of soil at the end of the previous day and S was the total storage capacity of the same layer.

For the present study estimates of soil moisture availability were derived using the program WATBAL developed at the Division of Land Research, CSIRO, Canberra (McAlpine, 1970). This simulation model was developed for the pasture situation and so does not consider the soil as a series of layers which are successively depleted by evapotranspiration as described above, although this is probably closer to reality for a tree crop. The model estimates soil moisture storage on a weekly basis with several subroutines to analyse the data in various ways. Since the latter are not relevant to this study they will not be described here.

Outline of the System WATBAL.

The following outline is based on the description of the system by Keig and McAlpine (1969b). Data required as input are daily rainfall and weekly evaporation. Rainfall provides the accessions to soil moisture storage and evaporation is used to estimate actual weekly water withdrawal from soil moisture storage. Rainfall is recorded for 52 standard weeks per year, each standard week having seven days except for week 30, which has eight days (Keig and McAlpine, 1969a). Eight days are also assigned to week nine in each leap year. The weekly evaporation figures used in this study were long term means, although it is possible to use actual evaporation data for the relevant season if they are available. Limited testing at the Division of Land Research has shown that the differences which result from using mean or actual weekly values are not great, since weekly rainfall is considerably more variable than weekly evaporation.

The model requires an estimate of maximum soil moisture storage (MAXST) and it is assumed that no runoff or deep percolation occurs until this maximum storage level is reached. In this study MAXST was estimated by applying data for known soil depth to an empirical table relating available soil water storage capacity to different soil textures and horizon thicknesses (Haantjens, 1969).

To determine actual weekly water demand (NDMD) by the vegetation cover, the relationship (potential evapotranspiration coefficient - PETCF) between maximum evapotranspiration and evaporation (EVAP) must be established for each week of the year. Derivation of a set of values of the PETCF is considered in the following section.

The estimated water demand by the vegetation on the soil moisture store for any one week, in contrast to the potential demand given freely available water, is calculated by a step function in which:

(a) the dependent variable is the actual evapotranspiration coefficient (AETCF), and

(b) the independent variable is the ratio of the sum of the soil moisture storage level for the previous week, NSTR (N-1), and weekly rainfall, NRAIN(N), to maximum available soil moisture storage, MAXST, expressed as a percentage. If this percentage is greater than 100 it is set equal to 100.

That is, water demand for week N is given by

$$\mathrm{NDMD(N)} = \mathrm{AETCF(N)} \times \mathrm{PETCF(N)} \times \mathrm{EVAP(N)}$$

where AETCF(N) is dependent on $\dfrac{\mathrm{NSTR(N-1)} + \mathrm{NRAIN(N)}}{\mathrm{MAXST}} \times 100$

Soil moisture storage level for week N is derived as follows:

$$\mathrm{NSTR(N)} = \mathrm{NSTR(N-1)} + \mathrm{NRAIN(N)} - \mathrm{NDMD(N)}$$

but if NDMD(N) is greater than NSTR(N-1) + NRAIN(N) then NSTR(N) = 0

If NSTR(N) is greater than MAXST, the amount by which it is greater is defined as water surplus lost to the system as runoff and deep percolation and then NSTR(N) = MAXST.

Derivation of Values of the Potential Evapotranspiration Coefficient.

Under normally drained forest stands uptake of water (ET) proceeds at the maximum rate for given weather conditions when soil moisture is at or close to MAXST. As the soil dries out the ET rate decreases, hence the relationship of ET to soil moisture status becomes important in calculation of trends in water availability. There is little published data on this for any tree crop and none at all for P. radiata. Kramer and Kozlowski (1960) indicated there could be variation in behaviour with changes in soil moisture between species even within one genus. This variation might possibly be associated with differing patterns of root distribution.

Rutter and Fourt (1965) found the potential evapotranspiration rate for Scots pine in southeastern England was 1.2 times the rate of open water evaporation (ie. PETCF = 1.2). The potential rate was operative until most of the available water was used; at lower soil moisture contents evapotranspiration continued at 10 percent of the potential rate (PETCF = 0.1).

Zahner (1967) proposed empirical expressions for the response of water uptake, as a fraction of potential transpiration, to falling soil water content, for soils of different texture. Uptake was assumed to equal PE until 33 percent of the available water has been withdrawn from a clay soil, 50 percent from a loam and 75 percent from a sandy soil. Below these points daily depletion equalled PE multiplied by the factor $\left(\frac{\text{current soil moisture level}}{\text{total storage}}\right)$. The latter can be recognised as basically the same algorithm used in WATBAL. Zahner presented evidence that this approach gave highly satisfactory results in southern U.S.A.

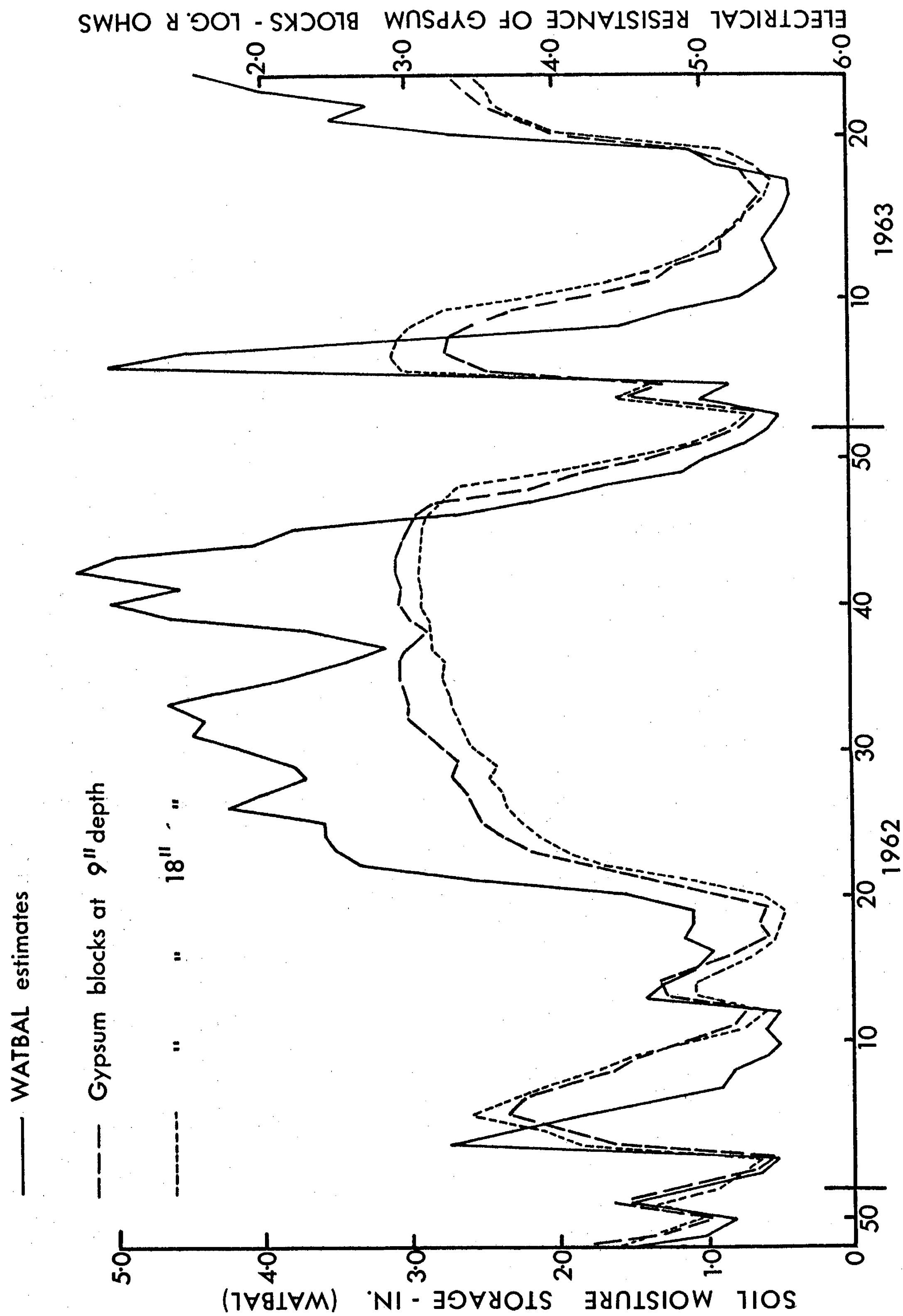
The evidence suggested, therefore, an upper limit for the PETCF of 1.2 (Rutter and Fourt) or 1.0 (Zahner) at 100 percent soil moisture content, and a lower limit of 0.1 (Rutter and Fourt). It has been shown (Johnston, 1964) that P. radiata has developed water conserving attributes which enable it to withstand drought for a considerable period and the species can reduce transpiration to a very low level. On this basis it seemed reasonable to set a PETCF lower limit of 0.1 at 10 percent of MAXST. The moisture release curves given by Zahner (loc. cit.) indicated at least two more intermediate "break points" were necessary to describe the changes in PETCF as soil moisture declined. Breaks to 0.4 at 40 percent of MAXST and to 0.2 at 20 percent were consequently adopted.

WATBAL was then tested against estimates of soil moisture availability obtained with gypsum electrical resistance blocks. The blocks had been used by Shepherd (1964) in his study of the effect of drought on cambial activity of P. radiata at Creswick, Victoria. The soil type was a sandy clay loam, the texture becoming somewhat heavier with depth down to 48 inches. From the table previously mentioned (p.133) the maximum soil storage was estimated as 7.0 inches. The gypsum block data were the averages for nine blocks at each of the depths 9, 18, 30 and 48 inches.

Daily rainfall and gypsum block data were available for part of the 1962 growing season and all of the 1963 season. Unpublished data from Shepherd indicated that canopy interception of rainfall in this stand averaged five points (0.05 inches) per rainfall event. Accordingly, five points was deducted from the total rainfall for each "rain day". Falls of five points or less were deleted.

It was established that an upper limit of 1.2 for the PETCF was excessive. The sequence 1.0 at 100 percent / 0.4 at 40 percent / 0.2 at 20 percent / 0.1 at 10 percent of MAXST gave good results (see Figure 9-1). The gypsum block data for 9 and 18 inches depth only are plotted as the data for the blocks at the greater depths followed a similar pattern (see Shepherd, 1964). An exact

FIG. 9 – 1 Comparison of soil moisture storage estimates by two methods.



comparison between the two sets of data cannot be made as the resistance block figures cannot (in this instance) be converted to estimates of actual soil moisture content. Nevertheless the WATBAL estimates faithfully reproduce the trends indicated by the gypsum blocks. The only significant deviation appears to be in the rate of depletion after the midsummer rains in 1962 and 1963.

The WATBAL estimates were highly correlated with the gypsum block data at 9 inches depth and were progressively less well correlated with blocks at 18, 30 and 48 inches. The simple correlation coefficient between gypsum blocks at 9 inches depth and WATBAL estimates was 0.88, which is considered very satisfactory in view of the poor sensitivity of gypsum blocks at high soil moisture contents.

The intermediate PETCF values for the sandy clay loam at Creswick are in substantial agreement with those arrived at by Zahner for the same soil texture.

9.2 Water Availability and Variation in Density Within the Annual Sheath.

Smith and Wilsie (1961), in their analysis of entire annual sheaths of wood from ground level to the tip of 55-feet tall loblolly pine, showed that soil water deficits had a profound effect on the distribution of wood density and latewood percentage within the sheath. Seasons of low water deficits were characterised by a large gradient in latewood percentage (and therefore, density) from apex to base. In seasons of higher water deficits the gradient became lower in direct relation to the severity of the deficit. In a season of extreme drought the gradient actually reversed, ie. the sheath was higher in latewood percentage and density at the top than at the base.

Such a relationship between seasonal water availability and variation in wood density within the annual sheath does not appear to hold for P. radiata, at least under the conditions encountered in this investigation.

Data from the 18 trees used in the within-tree study of Chapter 7 were subjected to further analysis. It will be remembered that nine trees were unfertilised and nine were treated late in the 1963 growing season with four cwt. each of superphosphate, potassium chloride and ammonium nitrate. The trees were of a size similar to those used by Smith and Wilsie. Density data were available at intervals of about four feet from the butt up to 80 percent of tree height, where the diameter underbark was about 1½ inches for most trees. Total height was available only for the year of sampling, but the distance from the base to any top diameter limit could be calculated by a computer program (see Appendix I). It is reasonable to assume the distance from this point to the apex would remain constant, or nearly so, during the juvenile and adolescent periods of growth. The height at which the top diameter limit was one inch (underbark) was calculated for each tree for each growing season from 1967 back to 1962. This involved a small error for the 1967 sheath since the wood samples did not extend to that point.

As a first step the linear regression of mean ring density on distance from the top diameter limit was calculated for the 1967 sheath for each of the 18 trees. Although the regressions differed in level between trees, especially between unfertilised trees, there was a strong trend for the slopes of the regressions to be very similar within each group of trees (Fig. 9-2). The average

FIG. 9-2 Individual tree regressions of mean density on distance. from top for 1967

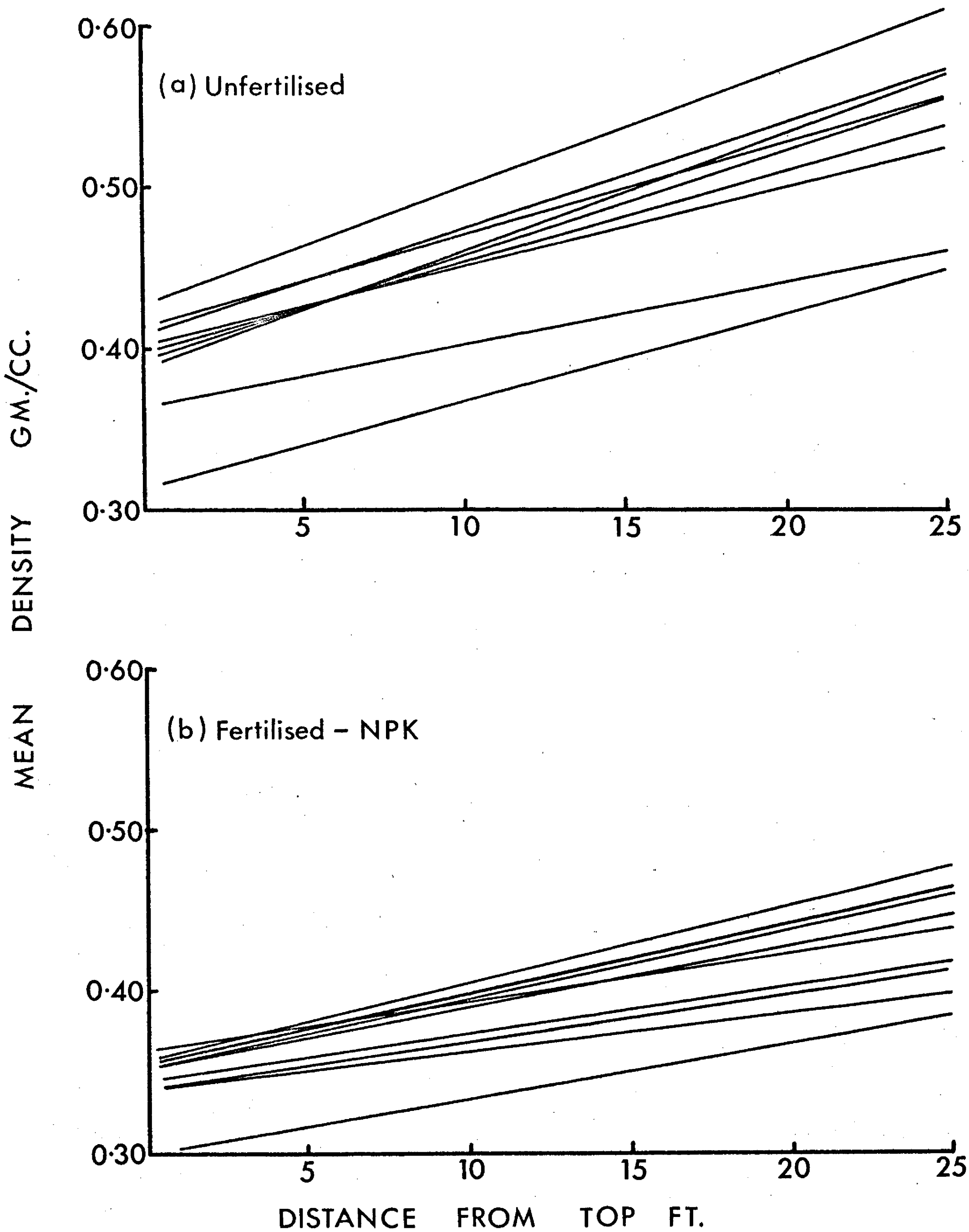
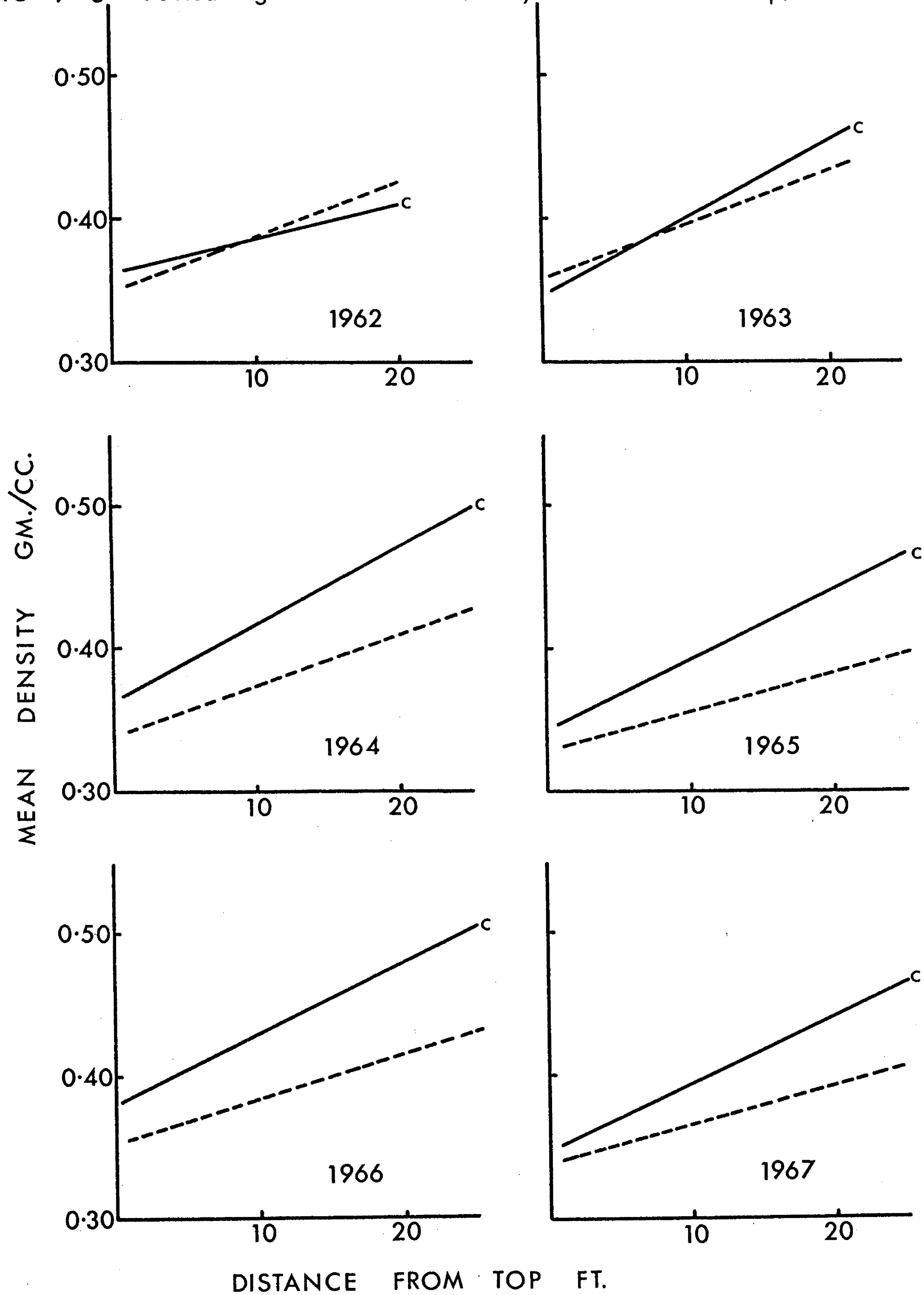


FIG. 9-3 Pooled regressions of mean density on distance from top.



correlation coefficients for the unfertilised and fertilised trees respectively were 0.944 and 0.893. Since main interest attaches to the slope of the regressions rather than the levels, and the slopes were very similar between trees in a group, the data for the trees in each group were pooled and group regressions, one for the fertilised and one for the unfertilised trees, calculated for each sheath from 1962 to 1967 (Fig. 9-3).

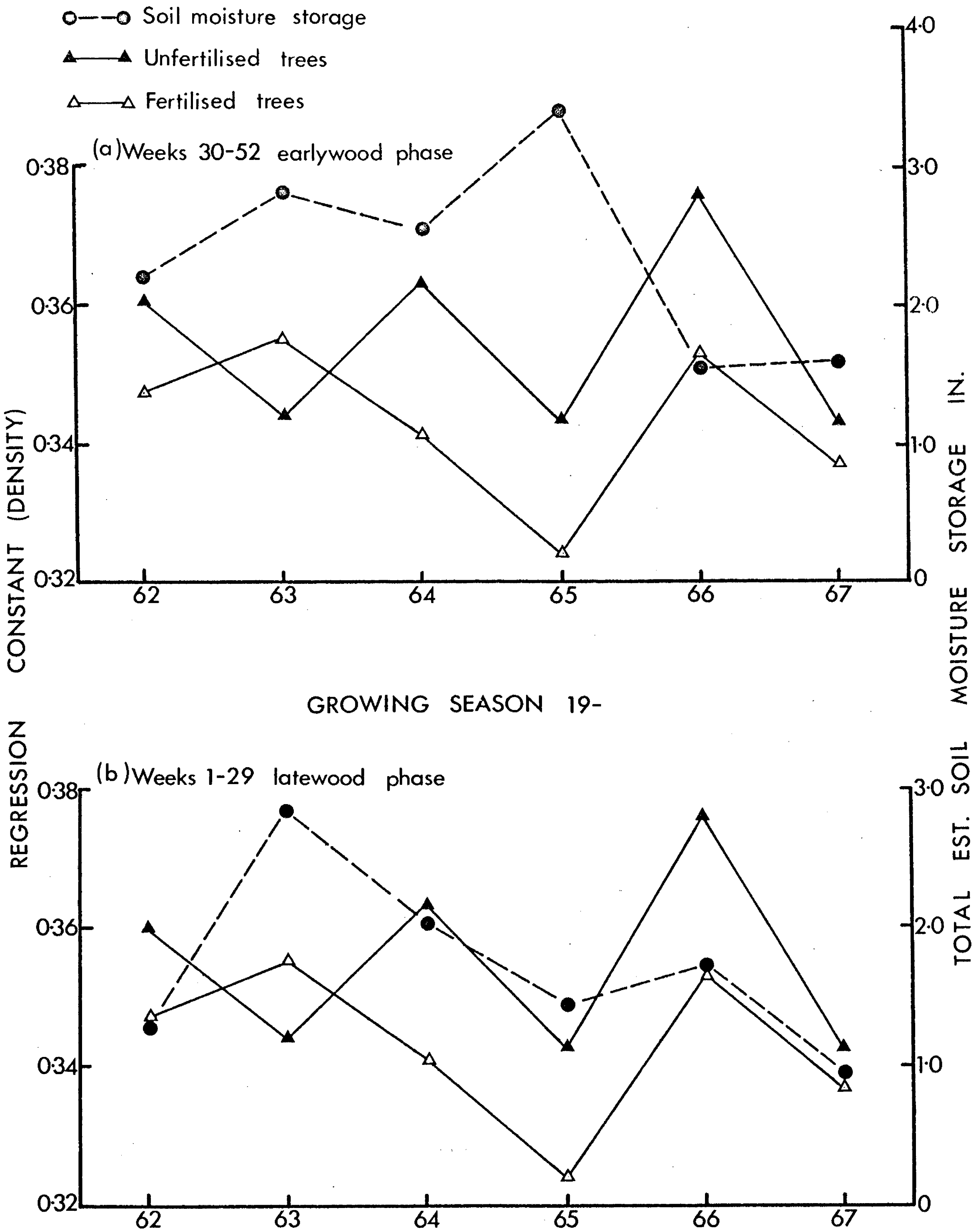
In 1962 there was no difference between the regressions, thus confirming the validity of the pooling procedure. In 1963 they began to diverge in slope, and from 1964 onwards they differed considerably in slope and level. The regression equations and the variance ratio for the test of common regressions are given in Table 9-1.

TABLE 9-1 Regressions of mean density on distance from top for each sheath 1962-1967

Sheath	Fertilised	Unfertilised	F-ratio(a)
1967	Y=0.337+0.0029D	Y=0.343+0.0049D	19.23 **
1966	Y=0.353+0.0032D	Y=0.376+0.0052D	17.36 **
1965	Y=0.324+0.0029D	Y=0.343+0.0048D	13.00 **
1964	Y=0.341+0.0033D	Y=0.363+0.0054D	11.07 **
1963	Y=0.355+0.0038D	Y=0.344+0.0054D	4.83 *
1962	Y=0.347+0.0038D	Y=0.360+0.0024D	1.93 NS

Note: (a) Test for slopes

FIG. 9 – 4 Effect of seasonal water availability on wood density.

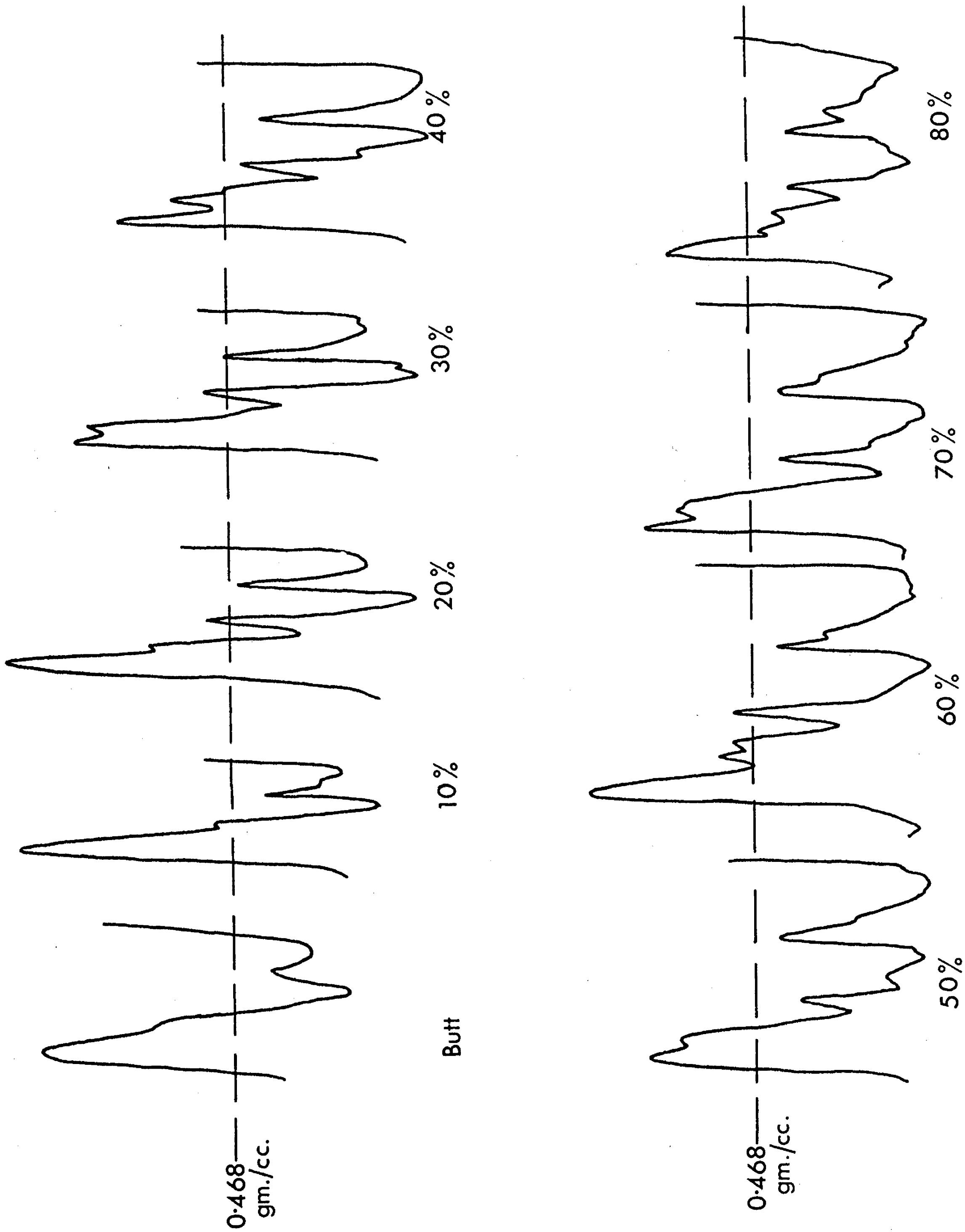


For the unfertilised trees the slope of the regression lines remained almost constant after 1962, however, the regression constants varied considerably from year to year. As found by Smith and Wilsie, this variation could be related to soil moisture availability. In Fig. 9-4a and b the regression constants are plotted against time, along with total available moisture (as estimated by WATBAL) for the weeks 30-52 and weeks 1-29 (the earlywood and latewood phases of growth respectively).

The greater the total moisture availability in the period of earlywood growth the lower the value of the constant for the unfertilised trees. This relationship held for every year except 1967, in which the existing environmental balance was modified by a thinning late in the 1966 season. Average stocking on the plots was reduced from 742 to 486 per acre thus making more moisture available to each tree. If the measure of water availability is changed to average amount per tree, the 1967 data fit the pattern of previous years.

By contrast there was only a weak positive association of the regression constant with water availability for weeks 1-29 for the unfertilised trees. For the trees which had been fertilised with NPK there was a much stronger relationship (see Fig. 9-4b). This is in agreement with the stronger correlations of density with February-March rainfall for fertilised trees described earlier in the KCl experiment. However, the regression constants (that is, density) for the NPK trees were less well related to earlywood season moisture availability, due to an anomalous value for 1963. It is suggested this was caused by the very rapid response to N in the fertiliser mixture, the effect being greater at the base of the sheath than at the top (see Chapter 7).

FIG. 9-5 Variation in the within-ring pattern of wood density with height in the tree.



The slopes of the regressions shown in Fig. 9-3 are very significant. Within each of the two groups of trees very variable moisture availability and heavy thinning in the years studied did not have any important effect on the regression coefficients. Only a heavy fertiliser application had any effect on the coefficients but even so the changes in density were not of the magnitude recorded by Smith and Wilsie. Apart from fertilisation these variations in environmental conditions did not affect the pattern of wood formation differently in the upper and lower stem. This is demonstrated by Fig. 9-5, which shows the density curves for the 1966 ring at nine levels in one randomly chosen tree. It is seen that the basic pattern of within-ring density variation remains the same from the butt to 80 percent of tree height.

Unlike loblolly pine, changes in wood properties in the lower bole of P. radiata are truly representative of changes in the whole sheath concerned. Therefore the results of investigations of wood properties at the intra-increment level, based on breast height sampling, can confidently be applied to the sheath as a whole.

9.3 The Relationship of Wood Density Within the Ring to Water Availability.

Introduction.

It has been demonstrated for many conifers that latewood development is directly related to the amount of moisture available during the period of latewood formation. Chalk (1951) observed this for Douglas fir grown in England

and suggested that closely spaced stands might form less latewood due to less available moisture per tree. Zahner, Lotan and Baughman (1964) reported that irrigation of red pine prolonged the period of earlywood formation by two months and increased the production of latewood, compared with trees subjected to artificial drought. Midsummer irrigation of 100-year old ponderosa pine over a seven-year period resulted in up to 40 percent more latewood than in trees not watered (Howe, 1968).

In the present study mean ring density was highly correlated with rainfall during the period of latewood growth (February, March and April) in the Flynn Creek KCl experiment (Chapter 6). The use of rainfall *per se*, has been criticised by Zahner and Donnelly (1967), who advocated the use of data on availability of soil moisture instead. However, on the sites used in this study, there was usually zero, or nearly zero, soil moisture storage by the end of each calender year, and growth in the latewood phase was directly dependent on the accession of water to the system via rainfall. Since wood density was highly correlated with latewood development there was a good relationship between density and late summer rainfall. Nicholls (1967) observed a similar relationship between summer rainfall and density and latewood percentage for *Pinus pinaster* Ait. in Western Australia.

Maximum ring density was shown to be negatively correlated with total rainfall for the months of August, September and October for *Abies grandis* Lindl. by Polge (1965b), and with the July - September total for *Picea sitchensis* Carr. in Scotland by Brazier (1969). Polge and Keller (1968), investigating the influence of irrigation on density variation within the ring in Scots pine, concluded that insufficient rainfall in the early part of the growing season brought about an increase in the minimum density. A severe water deficit occurring before the beginning of latewood production led to an increased maximum density.

So-called "false rings", or subsidiary bands of latewood type cells, have been observed to form as a response to drought (Dobbs, 1953, Shepherd, 1964) or some other drastic experience, such as defoliation (Mott, Nairn and Cook, 1957).

Harris (1955) was able to relate the sharpness of the earlywood-latewood transition to water availability at the time of transition, a dry period causing a sharp distinction between the zones. Subsequently Zahner and Oliver (1962) related the degree of production of large diameter (non-flattened) latewood tracheids to the rate of increase of internal moisture stress in red pine. Under slow rates of increase in moisture stress more large diameter and fewer small diameter cells were produced. The Meyer-Wegelin hardness feeler was used by Mammen (1952) to establish a relationship between proportion of latewood and seasonal rainfall. Hardness of latewood (equivalent to average latewood density) was positively correlated with summer temperatures but often negatively associated with summer rainfall.

Shepherd (1964) demonstrated the dependence of cambial activity on water availability in 30-year old P. radiata. Some of the trees used by Shepherd were still in existence and since dendrometer measurements at weekly intervals for the complete growing season 1962-1963 were available they provided excellent material for densitometric study.

The use of dendrometer growth records in studies such as this has been criticised (for example, by Zahner, 1968) since the dendrometer records the sum of cell division, cell expansion and stem hydration. In addition, all these are recorded for both phloem and xylem, whereas only the latter is of interest in this context. However, the usual alternative of regular tissue sampling is also subject to error due to tree-tree variability (where sampling has to be spread over several trees). An experiment along these lines at Flynn Creek had to be abandoned because of this factor.

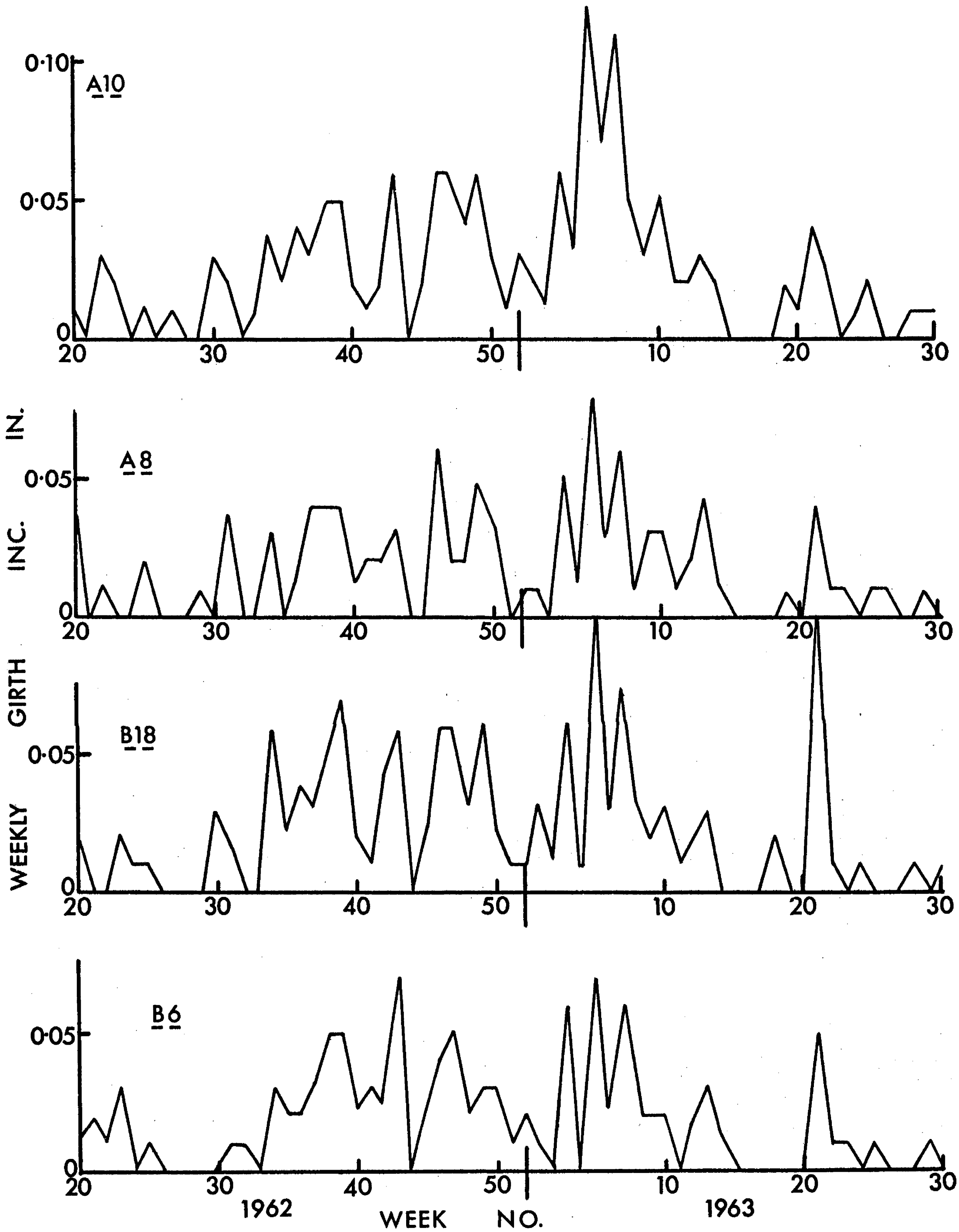
In the present study the stem hydration effect was allowed for by recording as increment only those measurements which exceeded previous maxima. It had to be assumed that phloem growth was the same relative proportion of xylem growth throughout the growing season. Phloem growth is small relative to xylem production so any error involved is slight.

The validity of investigations of this kind at the breast height level only has been questioned on the grounds that the effect of water availability on xylem development is quite different in the upper and lower stem (Zahner, 1968, citing Smith and Wilsie). It was established in the previous section that such a relationship does not apply to P. radiata.

Methods.

Two trees in each of Shepherd's plot A and plot B (the plots adjoined one another, see Shepherd, loc. cit.) were selected from the dendrometer records as showing the best growth for the 1963 season. They were sampled at the mid point of the internode in which the breast height point fell. Density tracings for each sample were obtained by the methods described in Chapter 2. For the 1963 ring

FIG. 9-6 Weekly girth increments for the four Creswick sample trees 1963 growing season.



special tracings were made using the 20x ratio arm on the densitometer, a very small beam width (0.05 mm.) and the slowest possible film carriage speed.

The dendrometer increment data were allocated to the same standard weeks used for the WATBAL data. From an examination of the increment data for each tree (Fig. 9-6) week 30 was nominated as the first week of the 1963 growing season (at breast height). The weekly increment data were then used to date the wood density tracings as follows:

(i) for each "growth week" from week 30, 1962, to week 29, 1963 the cumulative total girth increment was calculated,

(ii) the proportion of the grand total girth increment represented by this cumulative total for each week was applied to the total increment width of the 1963 ring on the density tracing,

(iii) and the wood density at each week was given by this calculated distance along the baseline of the density tracings.

For example, if for week 43, the cumulative dendrometer increment had been half the total dendrometer increment for the season, and the width of the increment on the density tracing were two inches, then wood density of the maturing xylem at week 43 would have been that at one inch along the baseline of the density curve from the commencement of the ring. In this way density for each growth week of the season was read off for each of the four samples.

FIG. 9-7 Weekly variation in wood density and soil moisture storage 1963 season, plot B.

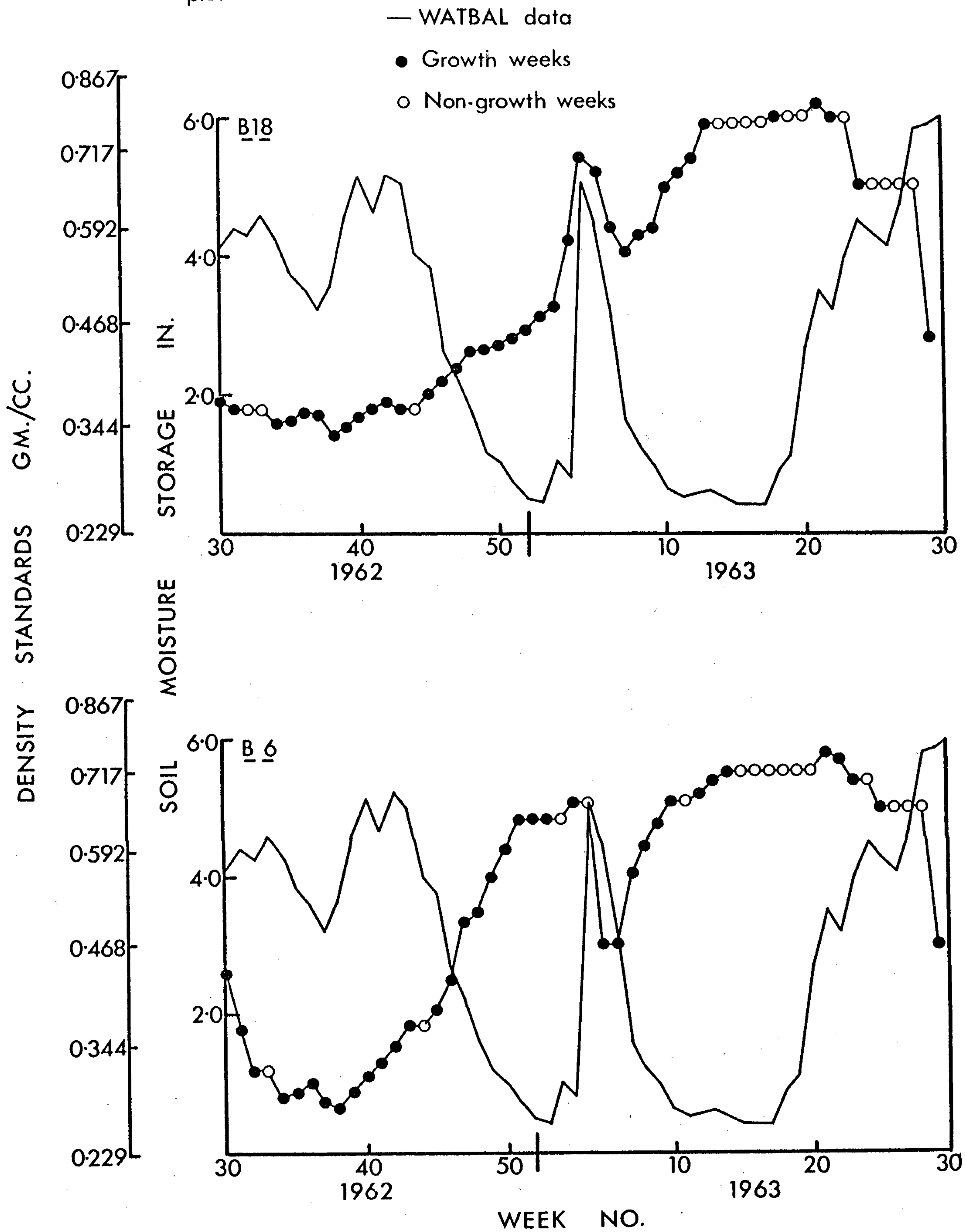
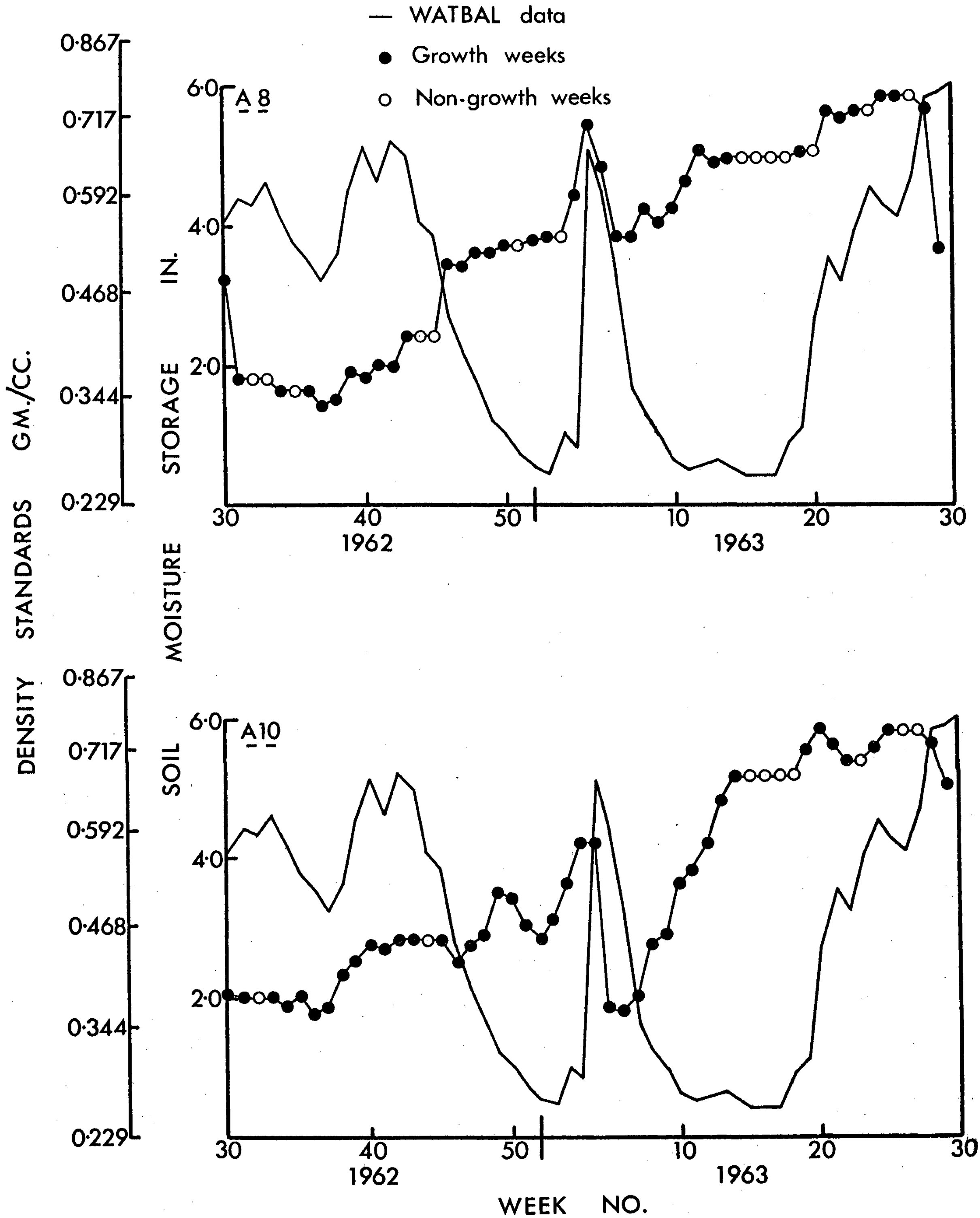


FIG. 9-8 Weekly variation in wood density and soil moisture storage 1963 season, plot A.



Results.

The density data thus obtained were plotted on the same linear scale as used for the WATBAL estimates of water availability (Fig. 9-7 and 9-8). Weeks for which there was no increment have been shown by empty circles while growth weeks have been shown by full circles.

The 1963 season was an interesting year in which to examine the effect of variable water availability on wood density. Soil moisture storage fell rapidly after week 42 to a level of 0.4 inches in week one; in week four there was very heavy rainfall and storage leapt to 5.1 inches, thereafter falling off rapidly again to 0.45 inches in week 11. Normal winter recharge did not commence until week 17.

Wood density in all trees was at a low level from week 30 to week 40, but thereafter began to rise in all trees, although more rapidly in some trees than others, for example, tree B6. Density reached a subsidiary peak in week four and then began to fall again in week five in every tree, following the rise in soil moisture storage in week four. After week six density began to rise again and continued to do so until growth ceased temporarily in either week 13 or week 14, as available soil moisture was again virtually exhausted. Only a small amount of growth was recorded following the commencement of the winter moisture recharge, and this was all at a high level of wood density, the peak values for the ring in all trees being reached in week 25 for the two trees in plot A but in week 21 for the trees in plot B.

Following this peak, density began to fall in all trees, although the trend was much more marked for the two trees in plot B. This decline in density in the closing

FIG. 9-9 Relationship of wood density to cell diameter and double-wall thickness, plot B. Non-growth weeks shown by blank symbols.

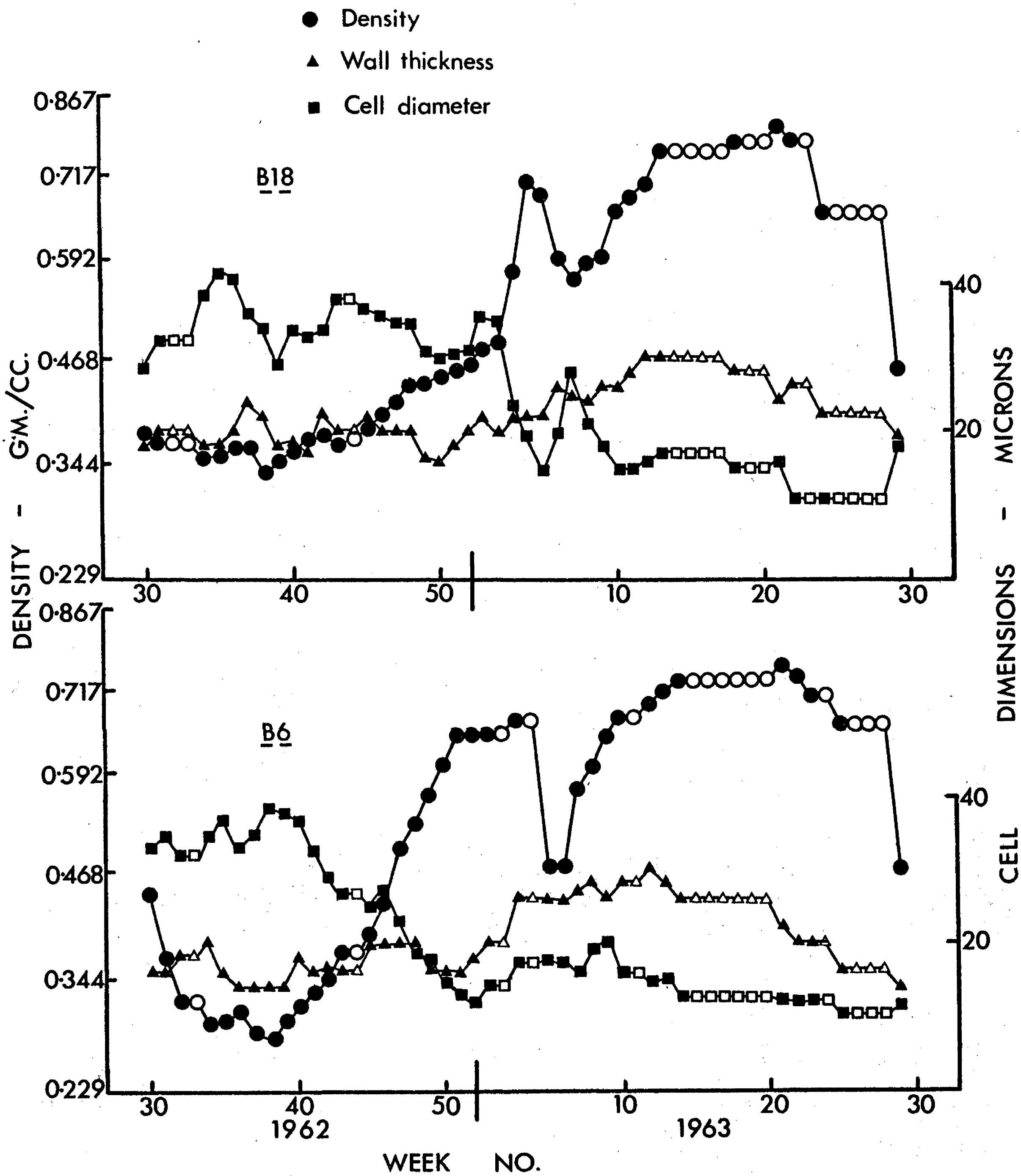
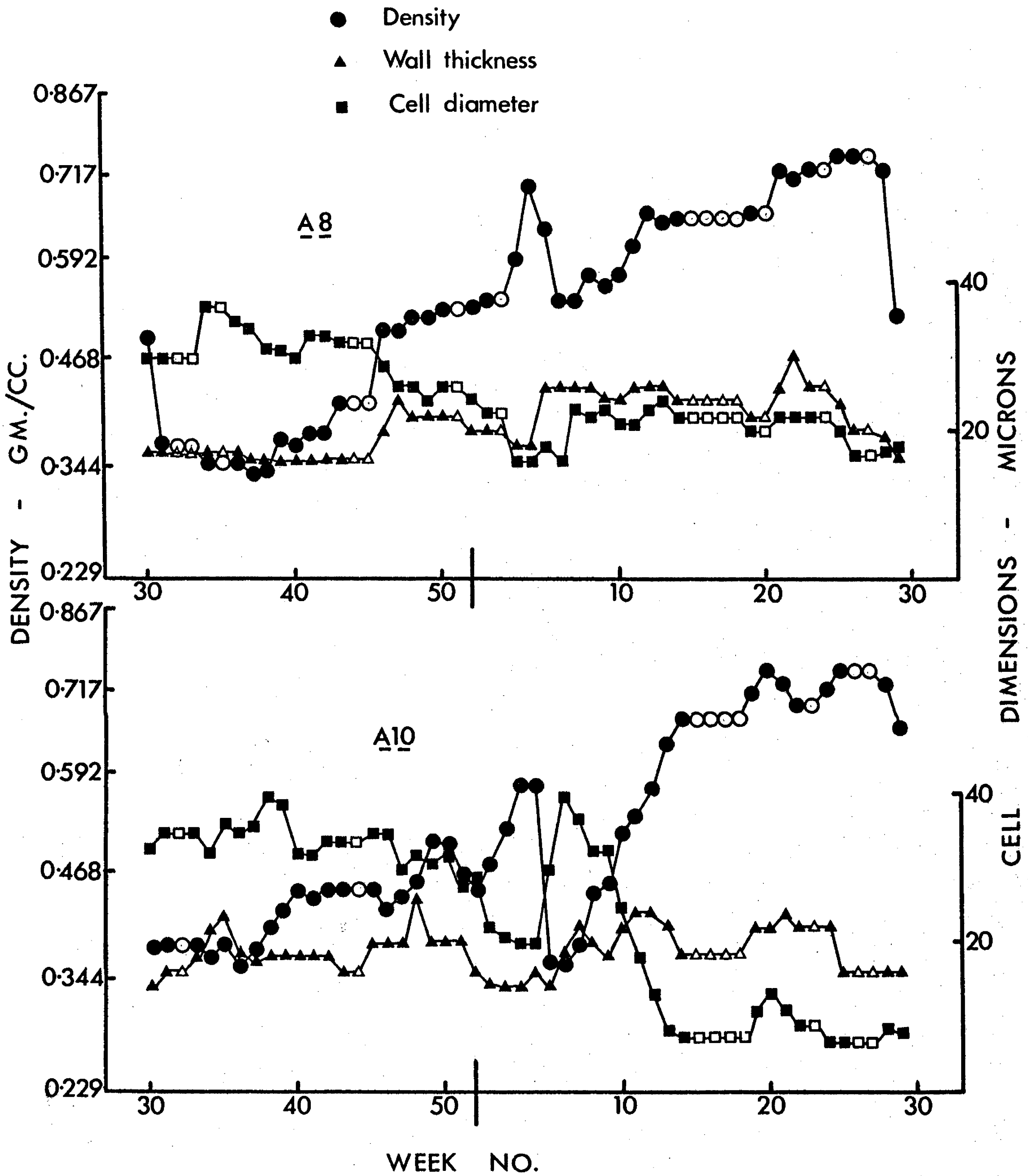


FIG. 9-10 Relationship of wood density to cell diameter and double-wall thickness, plot A. Non-growth weeks shown by blank symbols.



weeks of the growing season was thought to be either,

(a) a real effect due to declining cell wall thickness caused by lower net assimilation at that time of the year, or

(b) was an artifact, and the recorded increments were in phloem only.

The latter is most unlikely, as there is no evidence to suggest that in the pines phloem is capable of growth when xylem is not.

To check this point further, the wood samples were smoothed with a microtome and then examined on a dual-linear comparator (Smith, 1965). Radial cell diameter and radial double wall thickness were measured on two radial files of cells across the 1963 ring on each sample. The individual cell data varied considerably between adjacent cells, so in order to bring out the trends more clearly the data were "smoothed" by calculating a "running average" over groups of three cells. For example, the smoothed data for cell 16 was the average of cells 15 + 16 + 17. The data were allocated to the standard weeks by the same procedure described for the densitometric figures.

The cell diameter and wall thickness data, although based on a rather small sample, were consistent with the densitometric data over the whole ring. They confirmed that the fall in density in the last few latewood cells, noted above, was likely to be a real one. The general trend was for cell diameter to remain constant over the last few cells but there was a marked decline in double cell wall thickness in these cells, particularly in the two trees from plot B (Figs. 9-9 and 9-10).

According to Richardson (1963) variations in cell wall thickness can, for the most part, be attributed to changes in carbohydrate synthesis, although there may also be an effect of daylength independent of carbohydrate availability. There are no data on variation in rate of photosynthesis at Creswick but the general trend can be inferred from the solar insolation data from the nearest recording station (Highett, Vic.) and temperature data for Creswick (Table 9-2).

TABLE 9-2 Monthly average solar insolation and extremes of temperature 1963 growing season

Month	July	Aug.	Sept.	Oct.	Nov.	Dec.
Insolation(a)	674	871	1230	1693	2218	2347
Max. Temp.(b)	52	52	58	59	68	73
Min. Temp.	38	39	42	40	44	49
Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**
Insolation	2447	2032	1541	1223	574	538
Max. Temp.	77	71	69	62	55	50
Min. Temp.	52	47	48	42	44	39

Note: (a) Solar insolation on a horizontal surface in Btu/sq. ft.

(b) To nearest degree F.

During the period of the observed decline in cell wall thickness (May and June) and when wall deposition was taking place (May-July), solar insolation was at its lowest levels for the year and temperatures were not conducive to a high level of photosynthesis. Net assimilation over these three months was therefore at the lowest levels for the year and this is reflected in the amount of assimilate available for wall thickening.

Thus, an extrinsic factor other than water availability might have a significant influence on wood formation. As maximum density at Creswick occurred immediately before this decline it is likely water availability is not the dominant factor affecting maxima. As mentioned previously, Polge (1965b) and Brazier (1969) have shown a marked influence on maxima of total rainfall over a period of three months. In the present study it was also possible to correlate maxima with water availability (Table 9-3).

TABLE 9-3 Correlation coefficients of maximum density with weekly WATBAL estimates. Data for eight years.

Week No.							
19	20	21	22	23	24	25	26
-0.377	-0.671	-0.655	-0.707	-0.701	-0.733	-0.636	-0.470

The density data were the average of 20 trees from two ranked-set plots at Flynn Creek (180 miles east of Creswick). Before week 19 and after week 26 the correlation coefficients approached zero. Only the coefficients for weeks 22 and 24 are significant (at the five percent level).

At first sight these data might seem to support the conclusions of Polge and Brazier. However, the weeks in which the correlations are best are those in which a probable influence of solar radiation has been described above. The observed relationship may not, then, be a casual one. It is suggested these correlations might exist because high levels of soil moisture are associated with poor solar radiation, leading to reduced wall thickening of cells maturing at this time and hence a reduced maximum density. The evidence for this is slender but the possibility that it is so cannot be discounted.

The X-ray densitometric technique has been shown to be a very useful one in studies of this nature. Whereas more fundamental data can be provided by microscopic measurements of cell diameter and cell wall thickness, X-ray densitometry is much easier and more rapid.

The technique could have even wider application if the relationship between density and the other two parameters were the same between trees in a species. Unfortunately this is probably not so. The linear regressions of density for each "growth week" on the corresponding double cell wall thickness and cell diameter were calculated for each of the four sample trees from Creswick. In general, cell diameter was the more important component and was consistently highly correlated with density; the importance of double wall thickness varied considerably from tree to tree (Table 9-4).

TABLE 9-4 Correlation coefficients for regressions relating wood density to cell diameter and wall thickness

Sample Tree	Cell Diameter	Double Wall Thickness	Both (a)
A 10	0.938 ***	0.179 N.S.	0.940 ***
A 8	0.818 ***	0.771 ***	0.887 ***
B 6	0.924 ***	0.586 ***	0.954 ***
B 18	0.894 ***	0.731 ***	0.927 ***

Note: (a) Both diameter and wall thickness combined in a multiple regression.

The different relationship of wood density with cell diameter and cell wall thickness exhibited by the two trees in plot A appears to be real. It is true the data are limited but there is no reason to doubt the trend. Tree A 10 displays a marked correlation of wood density with cell diameter yet little correlation with double wall thickness, whereas double wall thickness was an important component of density in the other three trees. The reasons for this apparent anomaly are deserving of further research.

The variations in wood density accompanying the rise in soil moisture storage in week four are in good agreement with the results obtained by Shepherd on these plots in the previous season. The fall in density in week five is consistent with his observation that cells in the expanding layer at that time were able to mature with large diameters when the water deficit was relieved.

An examination of Figs. 9-7 and 9-8 shows marked differences between trees in the time certain levels of density were reached. Taking, as an example, a density level of 0.468 (which has been used in this study to demarcate earlywood and latewood), the week in which this density was reached in each tree was

tree A 8 - week 46,
tree A 10 - week 49,
tree B 6 - week 47,
tree B 18 - week 1.

This variation between trees is due partly no doubt, to genetic differences, but also partly to differences in the amount of water available to the individual tree.

While the present study has shown that major changes in water availability common to all trees are reflected by changes in wood density in the latewood phase, an explanation of the reasons for differences between trees at any point in time would require regular measurement of internal moisture deficits.

This study is the first attempt to explain within-ring variation in wood density in terms of the environmental factors affecting wood formation. Very similar results were obtained from four different trees to show that water availability has a dominating influence during the main part of the growing season. It is likely that other factors, such as solar radiation intensity, daylength and temperature become more important during the early and late stages of each seasonal increment.

CHAPTER 10

GENERAL CONCLUSIONS

10.1 Techniques.

The basis of the present study is the technique of X-ray densitometry. At the inception of this project the technique was partly developed and almost untried. In joint work with P. Rudman and M. Higgs the technique has been brought to the point of practical use. It has now been used in a variety of ways in these and other studies and has proved to be a most versatile and flexible method of assessment of intrinsic wood quality.

There are two possible approaches to the use of this technique:

(1) a more sophisticated approach to the conventional task of measuring average density at the intra-increment level. It has the advantage of providing information on extreme density values in the ring and the density range, or texture of the wood. This information cannot be given by gravimetric methods,

(2) assess wood quality in new and different ways by taking full advantage of the vast amount of information provided by the continuous record of wood density. For this new methods of analysis need to be developed, as forseen by Harris (1969 a, b). One possible approach would be to use advanced mathematical techniques such as Fourier

analysis to express the density curves in some mathematical fashion. This has recently been tried by Kawaguchi (1969) using microphotometric data.

In this study the X-ray densitometric technique has been used very much in the conventional manner, mainly for technical reasons. The densitometer used was found to be unsuitable for the attachment of the electronic accessories necessary to explore (2) above.

Nevertheless, an attempt was made to describe the form of the density curves by the use of a parameter called mean latewood percentage, defined as the average latewood percentage measured at four levels in the ring. The levels were density values chosen arbitrarily to span the usual range of density for P. radiata. This parameter was tested in two of the four fertiliser experiments studied.

In general, mean latewood percentage yielded very similar results to mean ring density and was, as expected, highly correlated with mean density. However mean latewood percentage did appear more sensitive to relatively small changes in the pattern of within-ring density variation. It is probably highly correlated with mechanical properties of wood and further investigation of this aspect is warranted.

The characteristic shape of the density curves for each annual increment for P. radiata (see Figs. 2-3 and 7-1), at least in the areas studied, was of great assistance in identifying the rings correctly. This is a valuable advantage of the technique. Errors due to incorrect ring identification are negligible.

A major consideration in this study was the use of biologically sound sampling methods. Because the growth habits of the species are somewhat different from those of other conifers in which sampling procedures have been investigated, it was necessary to confirm the validity of the proposed sampling methods. Different approaches to sampling were found necessary in small and large trees.

In small trees (height range 7-25 feet) sampling at a fixed percentage of tree height was found to give a marked improvement in precision over sampling at a fixed height above ground. Data from one only radial sample per tree were necessary.

In older trees, and where there were no great differences in development of the populations being compared, sampling at a fixed height gave satisfactory precision. In a study involving trees aged 13 years, samples at 10 and 20 percent of tree height did not yield a significantly better correlation with whole tree density than breast height sampling. However, in these larger trees it was found desirable to use two opposite radial samples per tree.

Where it is intended to compare wood density at points higher in the tree, percentile interval sampling was found to be inadequate. For this purpose sampling at equivalent growth stages behind the apex, as advocated by Richardson (1961), is essential, in spite of the practical difficulties involved with a varinodal species such as P. radiata.

An efficient method of selection of sample trees for the precise estimation of stand average wood density, ranked-set sampling, has been tested and used in one of the wood density studies. Developed by McIntyre (1952) for sampling pasture yields, it has not previously been used to estimate wood properties, but appears particularly well suited to this purpose. In stands aged 14 years at the Flynn Creek Tree Farm a "plot" of four trees (ie. one tree chosen from each of four sets of four trees, using diameter as the ranking attribute) was sufficient to estimate average stand wood density at breast height ± 0.020 gm./cc. at the 99 percent half confidence interval.

Ranked-set sampling provides an unbiased estimate of the population mean which is considerably more precise than the estimate from an equivalent number of randomly chosen samples. Hence for the same precision, sample size is reduced compared with pure random sampling - an important consideration.

10.2 The Wood Density Studies.

Wood density is the resultant of a complex interaction between external factors of the environment and the inherent genetic constitution of the tree. The dominant factors of the environment under the conditions in which P. radiata is grown in Australia, are nutrient availability and the seasonal pattern of water availability. These factors influence wood density both directly and indirectly via their influence on crown characteristics.

The effect of varying the nutrient status with mineral fertilisers on several aspects of wood density of P. radiata was intensively studied in four separate experiments in stands ranging in age from seven years to 20 years. In each experiment the addition of fertiliser had been followed by large growth responses. The results of these studies are summarised as follows :

(a) Both earlywood and latewood growth were stimulated by fertiliser treatment, but earlywood was always stimulated to a greater extent. As a result latewood percentage and mean ring density were reduced. Increasing quantity of fertiliser generally resulted in an increased effect on wood properties.

(b) Fertilisation increased the within-ring density range, usually by a reduction in minimum density in the ring, but sometimes combined with an increase in maximum density.

(c) The reductions in mean density and minimum density by fertilisers were greatest in the lower bole, decreasing progressively up the bole and becoming negligible at the top.

(d) A combined NPK fertiliser (four cwt. of each) caused a highly significant increase in stem taper and a similarly marked change in the breast height-whole tree density relationship.

(e) Fertilised trees were more responsive to variations in environmental conditions. The development of subsidiary peaks on the density curves ("false rings") was accentuated.

(f) Specific nutrient elements were shown to influence density in different ways. They may influence density without an associated height or diameter growth response.

(g) The fertilised trees generally had a more gradual gradient in mean density from the pith outwards.

(h) Contrary to the findings of Posey (1964) initial wood density of a tree did not influence the magnitude of its response in density following fertilisation.

(i) The effect of fertilisers on wood properties was the same for all sizes of tree in a stand.

(j) The duration of a wood density response to fertiliser treatment was at least 10 years in one study. In all four fertiliser studies the response was still very marked at the end of the study period.

According to Klem (1968) different composition and amounts of fertilisers do not influence wood properties differently except for effects directly related to differences in growth rate. For mean density this is probably so under most circumstances, but it is certainly not so in respect of maximum density. In these studies, nitrogen depressed maxima in two experiments when present in large quantities; phosphorus increased maxima in three experiments, and in one case did so without a concomitant diameter, height or volume response; potassium did not influence maxima in two experiments.

These investigations have shown, for the first time under field conditions, how the magnitude of the effect of a particular fertiliser on wood properties is determined by the balance of available nutrients. In the Belanglo "Super Trial" (Chapter 8) four cwt. of superphosphate markedly increased density maxima for a period of 10 years, yet at Flynn Creek the same quantity of superphosphate produced an increase which lasted only two years. This suggests some alteration of the nutrient balance had influenced the response of the trees, as it is inconceivable that the fertiliser could have been removed from the soil in this time.

The "Close Spacing" experiment at Belanglo (Chapter 5) provided further evidence to support this hypothesis. It was shown that the magnitude of the reduction in mean density by phosphorus was dependent on the availability of nitrogen, sulphur and a combined nutrient both separately and in combination. Furthermore, there is evidence from recent seedling studies (Murphey, Brady and Behan, 1969) of considerable alteration in physical and mechanical properties of wood caused by an imbalance in available nutrients.

The increase in stem taper and the greater reduction in density in the lower part of the bole due to fertilisation with NPK support the hypothesis that wood density and stem form are intimately related (Volkert, 1941, Turnbull, 1942, Schniewind, 1962). The reason for the association of taper and density is not clear, but a casual mechanism for the increase in taper is suggested as follows: The fertiliser stimulates crown growth, there are more needles and they live longer (Hall and Raupach, 1963). Thus there is a larger and heavier crown surface exposed to the wind, resulting in increased sway. Increased sway has been demonstrated to increase stem taper (Jacobs, 1954). This interpretation is supported by the positive correlation of stem taper with tree size observed in Chapter 3. The smaller trees in a stand have smaller crowns and are sheltered to some extent by the larger trees, so are less affected by wind forces.

Thus, the influence of fertilisers on wood properties is complex, being dependent on the nutrient elements involved and the balance of other available nutrients. Because fertilisers modify the within-tree patterns of density variation, investigations in this field need to consider both within-tree and between-tree effects.

There is a clear need for a greater understanding of the effects of fertilisation on physiological processes and the growth of the tree as a whole (Keller, 1968).

The influence of soil moisture availability on wood density was also investigated in some detail. It was studied in relation to patterns of density within the annual ring in four 30-year old trees from Creswick, Victoria, and in relation to variation within the annual sheath in 18 trees from Flynn Creek.

Variation in mean density with height in the tree in any annual sheath was not affected by large variations in seasonal moisture availability, although the slope of the density - distance from top regression was modified by fertilisation. Therefore, under normal growing conditions, the influence of water availability on wood formation is the same at all heights in the tree. This is contrary to the pattern observed in loblolly pine by Smith and Wilsie (1961).

The level of the density - distance from top regression was related to seasonal moisture availability. A dry August - December period produces a sheath of wood of higher density, as does higher than usual February - April rainfall. Hence a knowledge of the seasonal patterns of moisture availability, for example between two plantation areas, will enable a reliable prediction of how wood density will vary between the two areas, other factors being equal.

Soil moisture has a dominating influence on the within-ring density pattern for most of the growing season. The density of the expanding xylem was estimated at weekly intervals throughout the 1962-63 growing season using dendrometer records. With increasing moisture deficit from October to late November, density rose in all sample trees. When soil moisture storage was recharged by heavy rain in January, density fell markedly in all four trees in the following week, and then gradually rose again as moisture availability declined in succeeding weeks. These results were remarkably similar to those obtained by Shepherd (1964), who worked with the same stand in the previous growing season, but with a far more tedious technique.

The maximum density in the ring in the trees from Creswick was reached in late May or early June. From this date until the beginning of the next season's flush of growth, density declined in all trees. It was established this decline was due primarily to a reduction in double cell wall thickness in the last few cells of the increment. As soil moisture was not limiting at the time of expansion and wall thickening of those last few cells, it is likely other external factors such as temperature and solar insolation have a significant influence on wood formation at that time of the year. In the earlier part of the ring, cell diameter appeared to be the main component of wood density.

In the fertiliser experiments density maxima appeared to be dependent on some nutrient balance involving phosphorus. Possibly higher density maxima might be caused by increased cell wall thickening due to higher net assimilation in trees adequately supplied with phosphorus.

The effect on wood density of the combined expression of nutrient and water availability - site quality - was investigated in 14-year old stands at Flynn Creek. As a first step it was established that, although there was a trend toward a different density-height in tree relationship between sites, the differences were not statistically significant. However in older stands the differences might be greater and should always be evaluated in studies of this nature.

Site index did not influence weighted average density at breast height on either of the two main soil types at the Flynn Creek Tree Farm. However, an analysis of ring-by-ring trends in density revealed a negative relationship between mean density and site index developing on the deep sands but not on the shallow silty loam soil type. On the sands the pith-to-bark gradient in mean ring density tended to be inversely related to site index, but there was no such trend on the loams.

Whereas weighted average density did not vary with site index, it did vary considerably with soil type, being some 10 percent lower on the loam type. This difference was due to inherent characteristics of the soils and not to some differences in treatment between the two areas. Not only was mean density lower on the loam, but it was also less variable. The gradient from pith to bark was lower and the variation between trees was less. Density range was also consistently lower.

Thus, there can be no all-embracing conclusion that wood density is, or is not influenced by site quality. Whether site will have any effect on density depends on characteristics of the particular soil. Investigation of how these soil factors act and interact on wood density is a field which has been largely ignored.

10.3 Implications for Utilisation and Forest Management.

A reduction in wood density of the magnitude observed in this study, say 0.050 gm./cc., whether due to fertilisation or natural soil factors, represents a significant change in the quality of the wood.

The mechanical properties of lower density wood will be considerably poorer. Average modulus of rupture would be expected to be lower by some 14 percent (from 900 to 770 kg./cm.^{2}, see Sangüesa, 1965) and there would be similar reductions in bending strength, compression parallel to the grain and toughness (Klem, 1968). For most purposes for which P. radiata is used in Australia, these properties are not critical and any changes would go unnoticed. But a reduction of this magnitude could be important where bending strength is of consequence, for example in engineered structures and roof trusses. A reduction in density might even be an advantage for the plywood industry as less power would be required for peeling.

Wood quality for pulp and papermaking will also be affected. The implications for the pulp industry of a reduction in wood density have been the subject of much research in recent years. Briefly, the main changes are higher burst and tensile strengths but lower tear factor, opacity and bulk. However, printing papers made from lower density coniferous wood are smoother and tissue papers softer. The significance of a change in pulp properties varies with the process used and the ultimate product but higher density is generally equated with higher quality.

Although some important pulp quality indices are lowered, the product is not necessarily unacceptable as a result. Fahey and Laundrie (1968) compared kraft pulp, papers and linerboards from eight-year old thinnings and mature trees of loblolly and slash pines. They concluded the much lower density thinnings provided products at least as good as those from the old trees. Only tearing resistance was lower and this was still within the range of many commercially produced papers and linerboards.

The significance of changes in pulp properties also varies with species. Watson and Dadswell (1962) examined the effect on paper properties of varying the latewood proportion in pulp from 0 to 100 percent. They found variation in latewood percentage had little or no influence on burst, tear or bulk properties in P. radiata, but was important in loblolly pine.

Therefore, it is concluded the pulp and paper industry need not be concerned that fertilisation of P. radiata will significantly reduce the quality of the raw material. In fact, for some uses, quality may be improved.

A more serious aspect of a reduction in density is its effect on pulp yield, which is directly related to wood density (Mitchell, 1964). For the same pulp yield as obtained from higher density wood, it is necessary to cut, transport, debark and defibrate a greater quantity of lower density wood. The lower yield per digester charge in batch processes might be partly offset by lower power requirements for beating, but it is likely there will still be an economic penalty in processing.

In evaluating the overall economics of fertilisation the effect of the growth response on logging costs must also be considered. Since harvested volume per unit area is greater, logging costs will be reduced. The cost of logging significantly exceeds the cost of growing the timber (Hanson, 1966), so an important reduction in costs in this area would have a large influence on overall raw material cost. Hill (1966) has shown how even small differences in average log size in first thinnings have an important effect on logging costs. The significance of unit log size is not likely to diminish with the introduction of the highly mechanised logging systems now under development.

In recent years there has been considerable speculation on the possibility of controlling wood properties by forest management procedures. Thinning, pruning, planting espacement and genetic manipulation have been advocated as suitable methods of exerting control. Certainly some control is possible within the limits set by species characteristics.

If low density wood were particularly desirable, fertilisation is a feasible technique to achieve this end under suitable conditions. Alteration of the proportion of higher density wood in the tree by changing the rotation length is another convenient and effective approach.

Thinning can influence wood density to some extent. It appears likely thinning of *P. radiata* is associated with a reduction in density (Chapters 4 and 7). The method of thinning will also influence the variation in density between remaining trees. Most thinning of *P. radiata* in Australia is selective, favouring the more vigorous stems. Because of the inverse correlation of wood density with tree size, removal of the subdominant and suppressed stems will result in a stand with a lower average density and with less variation between trees.

Another important method of control of wood density is through genetic improvement, either by selection within the species or by regeneration with cuttings. Apart from the practical problems of selection of genotypes which have a desired wood property but still have the other essential traits of vigour and straightness, there is the question of which wood properties are desirable. Whereas the values associated with vigour and straightness are well known, there is little information on the values associated with a trait such as wood density. For this reason Namkoong, Barefoot and Hitchings (1969) concluded it is impossible for the tree breeder to decide how much effort to devote to changing wood properties.

There is considerable practical significance in the differences in wood density from trees grown on these two soil types at Flynn Creek. Firstly, because the trees were grown from seed from the same source and the stands had received virtually the same treatment, these results are a convincing demonstration of the magnitude of the environmental influence on wood density. The increase in density going from the loam to the sand type is equivalent to the highest likely gain from a tree breeding program aimed specifically at raising wood density (Namkoong, Barefoot and Hitchings, loc. cit.). Therefore a fundamental study of the factors which caused this difference might point to ways of modifying wood density which would be more rapidly, and perhaps more cheaply, implemented than by tree breeding.

Secondly, if either high or low wood density were a desired attribute, the wood properties of the crop can be controlled by concentrating planting or harvesting onto the appropriate soil type. Land acquisition policy would also be affected, as would land prices if a financial value could be placed on the desired wood property.

Because of the inadequate information on values to be assigned to wood properties, and because there is no certainty what is a valued feature in 1970 will still be so in 1990, the economics of any silvicultural measure designed solely to modify wood properties must be very doubtful. It would appear more practicable to ensure the existence of an adequate resource with a range of wood properties which can be blended to produce any required furnish.

In the opinion of this writer, it is immaterial what changes in wood density of P. radiata are wrought by fertilisation or any other silvicultural practice. The magnitude of any changes will be no greater than the natural variation between stands. In this species the growth responses to any cultural treatment will far outweigh any disadvantages due to a reduction in density. Therefore plantation management should be oriented solely toward growing the maximum quantity of cellulose per acre at the lowest total cost.

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APPENDIX I

Computer Programs Used in These Studies.

The programs detailed below were the main ones developed by the writer to process the data for these studies. In addition to these, a number of small programs were written to perform minor tasks but are not given here. Extensive use was made of ORTH1FCT and ORTH2FCT, two of a range of programs for statistical analysis developed for the CDC 3600 computer by the Division of Mathematical Statistics, CSIRO, Canberra.

Program WOODEN

Purpose: Calculate mean ring density from the basic measurements made on the density tracings and summarise the data in several ways.

Input: Individual film calibration regression constant and coefficients, dot counts (area under the density curves), and increment widths.

Algorithm:

1. Height intercept (H) $= \frac{\text{area under curve}}{\text{increment width}}$ for each ring in a sample.
2. Density (D) $= a + b(H) + c(H^2)$ for each ring.
3. Average the mean density of corresponding rings on opposite radii.

4. Calculate distance from pith to outside perimeter of each ring, averaging ring widths on opposite radii.
5. Sample weighted average density

$$= \frac{\Sigma_1^n \text{ (D x sectional area of ring)}}{\text{total sectional area}}$$

If required, subroutines could be called to punch out the input data for DENDRY or summarise the data by samples or treatments.

Maximum and minimum density were computed using an abbreviated version of this program.

WOODEN could also be used to calculate latewood percentage for the appropriate input by calling a special subroutine.

Program DENDRY

Purpose: Calculate whole tree weighted average density, tree volume and dry weight to any desired top diameter limit. By progressively deleting the data for the outside growth sheath the program calculates the volume and dry weight for as many sheaths as are nominated.

Input: For each sampling height in the tree, the distance from the pith (DFP) and mean density (D) of each ring, height above stump at which the samples were taken (H), number of sheaths to be "removed", top diameter limit (TDL).

Algorithm:

1. Height from stump to TDL is calculated as follows:

   H_1 and H_2 are two successive sampling heights on the stem, H_2 being the higher. $\frac{TDL}{2}$ is less than the DFP at H_1 but greater than the DFP at H_2. Assume a linear rate of decrease in diameter from H_1 to H_2, then

   $$\frac{DFP(H_1) - DFP(H_2)}{(H_2 - H_1)} = \frac{DFP(H_1) - \frac{TDL}{2}}{E}$$

   where E is the height by which the TDL point exceeds H_1.

   Hence $E = \dfrac{\left(DFP(H_1) - \frac{TDL}{2}\right) \times (H_2 - H_1)}{DFP(H_1) - DFP(H_2)}$

   and the height from stump to TDL = $H_1 + E$.

2. Calculate weighted average density at each sampling height (as in WOODEN).

3. Calculate volume of log (V_n) between sampling points as - $\left[\frac{S_n + S_{n+1}}{2}\right] \times L_n$ in cu. ft., where S represents sectional area and L the log length.

   Top log volume is $\left[\frac{S_n + S_{tdl}}{2}\right] \times E$

4. Tree volume (TV) is the sum of the log volumes.

5. Weighted whole tree density (WTV) derived by weighting the average density of the ends of the log by the log volume

ie., $$WTV = \frac{\Sigma_1^{n-1}\left[\left(\frac{D_n + D_{n+1}}{2}\right) \times V_n\right] + \left[D_n \times V_n\right]}{TV}$$

6. Dry weight of the tree = TV x WTV x 62.5 lb.
7. Repeat steps 1-6 deleting the data for the outside sheath, for as many sheaths as specified.
8. Volume and dry weight of each sheath is given by successive subtraction of whole tree data.

Program VOLS

Purpose: Calculate volume of earlywood and latewood in each annual sheath.

Input: Earlywood and latewood width for each ring at all sampling heights, heights at which tree sampled, TDL, number of sheaths for which data required.

Algorithm:

1. Calculate height to TDL for each sheath (as for DENDRY)
2. Average data on opposite radii.
3. By addition, calculate the distance from pith to outside perimeter of earlywood and latewood for each ring.
4. Calculate sectional area of earlywood and latewood in each ring and thence volume of earlywood and latewood in each sheath by the same process as in DENDRY.

APPENDIX II

Growing Season Rainfall at Flynn Creek Tree Farm

Growing season	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June
1961	404	267	222	180	510	179	58	119	249	188	126	288
1962	544	250	206	301	81	152	329	148	100	83	219	246
1963	234	341	363	211	127	239	374	196	132	127	639	227
1964	280	348	376	196	121	73	128	214	152	307	249	324
1965	470	665	394	364	193	305	77	15	130	418	135	96
1966	173	337	220	113	388	218	133	288	199	270	196	169
1967	351	187	196	264	318	452	114	49	254	42	183	172
13 year average	288	365	278	239	277	243	136	142	143	212	305	238

The recording station is located some 400 metres from the site of the fertiliser experiments studied in Chapters 6 and 7.

APPENDIX III

Reproduction of Paper published in the Journal of the Institute of Wood Science No. 24, 1969.

QUANTITATIVE DETERMINATION OF WOOD DENSITY BY X-RAY DENSITOMETRY

by P. RUDMAN,* F. MCKINNELL† and M. HIGGS‡

Summary

A modified procedure for the determination of wood density by X-ray densitometry is described and evaluated statistically. It results in an improved relationship between wood density and optical density of the X-ray negative. The application of the method is illustrated by using data from studies of phenotypic variation in *Eucalyptus regnans* and of the effects of fertilizer application to nutrient deficient *Pinus radiata*, differences in density of 0·036 g./cc. being statistically significant. In between species comparisons, the least significant difference could be higher, due to the greater error associated with the calibration curve.

Introduction

In recent years there has been increased interest in breeding trees with superior properties, particularly in relation to wood density. Polge (1963, 1965, 1966) recognised the need for greater detail in assessment of density and developed a new technique using X-rays. Variations in wood density produce corresponding variations in optical density on the X-ray negative. Wood density is derived from optical density by reference to a calibration curve, the X-ray negative being scanned by a recording microdensitometer.

The X-ray tube produces a spectrum of radiation with a peak emission wavelength varying inversely with the applied voltage. When wood is irradiated at low voltages the larger wavelength radiation is selectively absorbed giving a non-linear relationship between wood density and optical density so that determination of wood density is biased. Linearity can be improved by interposing a thin aluminium screen (0·6 mm) to attenuate the longer wavelength radiation in the emission spectrum. Since image resolution is greater with long wavelength radiation, X-ray densitometry involves a compromise between image sharpness and linearity of the wood density: optical density calibration curve. In addition to quality of the irradiation spectrum, the intensity of X-ray affects the exposure time for film of a given speed rating.

Thus, to obtain an X-ray negative suitable for accurate determination of wood density the following information is needed:

(a) the voltage which gives the best compromise between the conflicting requirements of sample thickness, attenuation of rays by the sample, and image resolution.

(b) the time necessary for correct exposure of a given film.

This paper reports modifications to Polge's technique which permit more accurate density determinations in both softwoods and hardwoods.

A calibration curve is derived by relating optical densities of a large number of standard wood samples to their known gravimetric densities. Since it is impractical to X-ray these wood samples with every routine wood density determination, more convenient working standards are required. Cellulose acetate is chosen as a suitable material and is calibrated in terms of wood density using the curve established for the standard wood samples. Errors in density determinations by X-ray densitometry are estimated and discussed in relation to variations in film quality and to variations associated with the wood density: optical density regression.

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Methods

Preparation of Standard Wood Samples

Thirty four wood blocks including diverse softwood and hardwood species were selected to give a wide density range. From each block a sample was sawn (10mm. $\times$ 10 mm. $\times$ 5 cm.) carefully orientated in the radial and longitudinal directions. The samples were conditioned to 8 $\pm$ 0·5 per cent moisture content in a closed container over a saturated solution of sodium dichromate which has a relatively constant aqueous vapour pressure at ambient temperatures. The conditioned samples were machined on the four faces to a final cross-section 6·9 $\pm$ 0·04 mm. using a Black and Decker router modified to work as a spindle moulder (Plate 1) with a tungsten carbide tipped cutter. The ends of each sample were smoothed with a plane.

In our work a sample thickness of 6·9 mm has been used because both softwoods and hardwoods have been examined. Hardwood samples of the thickness used by Polge, namely 5 mm., shattered easily.

Gravimetric density of each sample was based on oven-dry weight and its volume at 8 per cent m.c. which was calculated from measurements with a micrometer. This measure of density is intermediate between basic and air dry densities.

The samples were x-rayed in the radial longitudinal direction to minimise the effects of within growth ring variations.

Preparation of Cellulose acetate working standards

Cellulose acetate sheet, 0·8 mm. in thickness, was cut into 7 strips approximately 7 cm width and of lengths varying from 1 to 7 cm in steps of 1 cm. After dipping the strips in acetone they were pressed together forming a step wedge whose thickness increased progressively from 0·8 mm. to 5·6 mm. This large step wedge was then sawn into six replicate step wedges each 1 cm.

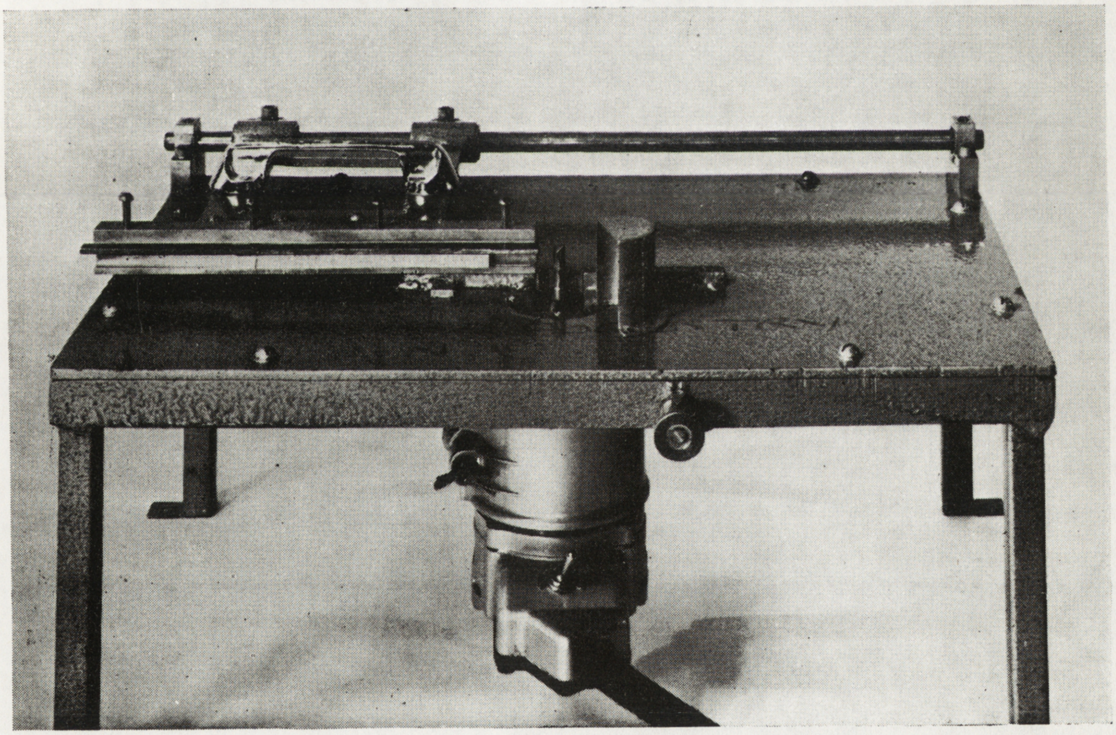

Plate 1.

wide. Hereafter, these cellulose acetate working standards are referred to as *step wedges* and the term *step* refers to an individual level of a step wedge.

X-ray Irradiation and Film Development

The wood samples and the step wedges were placed on top of a 20·3×25·4 cm. (10×8 in.) x-ray film, care being taken that no sample or the wedge was closer than 3-4 cm. from the film edge. To ensure parallel radiation the x-ray source was situated 2·5 metres from the film. Initially x-rays generated at 15 Kv were used, as suggested by Polge, but the resulting non-linearity of the wood density: optical density relationship was too great for accurate determinations. Subsequent irradiations were made at 23 Kv at 20 ma for a time which varied according to film speed (Fig. 1), with a 0.6 mm. thick aluminium screen interposed 25 cm from the source. Each film was developed for 5 minutes and fixed 5 minutes at 20°C with continuous agitation, washed thoroughly and rapidly dried.

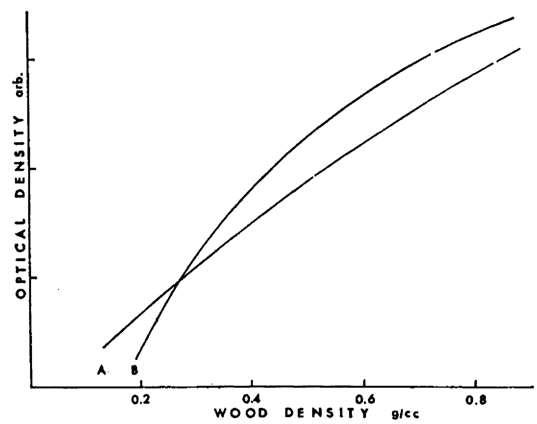

Figure 1 A comparison of wood density: optical density relationships. Curve A, 23 Kv., 20 ma., with an aluminium screen interposed. Curve B, 15 Kv., 20 mA.

Estimating Density from the X-ray Film

The optical contrast on the X-ray film is translated into a continuous chart recording using a Joyce-Loebl microdensitometer. This is the type used by Polge. Having adjusted the instrument to record from an arbitrary baseline the optical density of a sample is measured from it as the linear displacement. Mean optical density is estimated by measuring planimetrically the area beneath the curve and dividing by the width of the traverse. Defects in the available integrating unit for the microdensitometer have so far prevented its use in determining mean optical density. Two traverses with slight lateral displacement were made over the length of the samples and step wedges. Optical densities were determined as the mean of the two traces and for the sample, linear correction was applied for deviations from 6·9 mm. in the radial dimension.

Results and Discussion

The Wedge and Film Variability

Tests with step wedges on films of several different commercial brands showed important differences in the magnitude of background variability. When optical densities of samples were corrected for variations in background, corresponding steps were found to be almost identical, but the extra time is prohibitive for routine work. Only one brand of film was considered suitable for routine use without background correction and this brand was investigated more intensively.

The standard deviations in terms of density for six steps on six test films are presented in Table I and the analysis of variance in Table II. From Table I the film mean standard deviations (over all steps of the wedges) range from 0·003 for film 131 to 0·009 for film 65. Similarly, the mean standard deviations for each step range from 0·007 for step 7 to 0·005 for step 3, there being some indication, although not significant, of a linear trend. Within the limits of wood density from 0·344 to 0·867 the coefficients of variation range from 0·8 to 1·5 per cent. Thus optical density differences over a few centimetres are small and not significant; over greater distances in a film they may become highly significant. Film of this type is made on long, wide rolls and subsequently cut into sheets, and so the results obtained are consistent with the manufacturing process.

TABLE I Factors influencing the Standard Deviation of Cellulose Acetate Step Wedges*

Film No.	63	65	72	131	132	133	Mean S.d.	Coeff. Variat.	Std. Error†
Density level		Standard Deviation							
0·867	·007	·009	·008	·007	·006	·007	·0073	0·80	·0146
0·717	·004	·011	·007	·004	·007	·005	·0063	0·83	·0126
0·592	·003	·010	·008	·004	·006	·003	·0057	1·00	·0114
0·468	·006	·011	·008	·002	·005	·002	·0057	1·29	·0114
0·344	·072	·004	·007	·001	·005	·002	·0052	1·50	·0104
0·229	·011	·008	·005	·002	·005	·002	·0055	2·56	·0110
Mean S.d.	·0072	·0088	·0072	·0033	·0057	·0035	·0059		
St. Error‡		·0176					·0120		

Notes:
*S.D. – Standard Deviation; see text for details
†Based on n = 1 95 per cent confidence level

TABLE II Importance of Film Variability

Source of Variation	D.F.	S.S.	M.S.	V.R.
Within film	5	·000147	·0000294	5·34*
Within wedge	5	·000018	·0000036	N.S.
Errors	25	·000138	·0000055	
Total	35	·000303		

Notes:
*Significant at 1 per cent level; N.S. Not significant; since each film contained a number of step wedge density standards the N.S. result is indicative that the within film variation is not important over small areas such as those of the step wedges.

Calibration Curve

The relationship between wood density (Y g./cc.) and optical density (D cm.) was described by both linear and curvilinear regression (Fig. 2). The observations showed no consistent behaviour by softwood or hardwood species, but some itinerant samples exerted a strong influence on the error of each regression. Consequently, the linear and curvilinear regressions were based first on all observations and secondly on those observations within the wood density range 0·25 to 0·90 g./cc. Each regression with its error mean square (EMS) is shown in Table III; the curvilinear regression is an improvement over linear regression of 30 per cent when based on all wood samples and 20 per cent in the case of selected observations.

The wood density values assumed for the steps of the step wedges were derived from the curvilinear regression based on all observations. The values for steps 2 to 7 were respectively 0·229, 0·344, 0·468, 0·592, 0·717 and 0·867 g./cc.

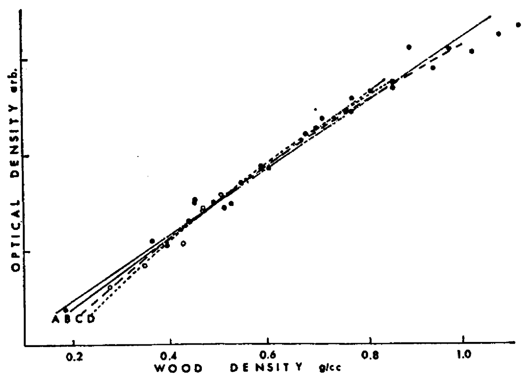

Figure 2 The wood density: optical density relationship for 23 Kv., 20 mA., A1 screen, showing gymnosperms ○ and angiosperms ● and the four regressions. A. Linear regressions (all observations); B. Linear regression (selected observations); C. Curvilinear regression (all observations); D. Curvilinear regression (selected observations).

Least Significant Difference Between Estimates of Wood Density

The least significant difference (LSD) is composed of two parts, one due to the error associated with the film variability, the other to error in deriving the calibration curve.

$$\text{LSD} = [2((\text{film optical density standard error})^2 + (\text{calibration curve standard error})^2)]^{\frac{1}{2}}$$

$$\text{LSD} = [2((0{\cdot}012^2 + \text{E.M.S.}))]^{\frac{1}{2}}$$

where the L.S.D. ranges from 0·036 to 0·055 g./cc. (Table III). The E.M.S. is obviously going to exert a considerably greater influence on the L.S.D. than is the optical density standard error of ·012 g./cc. It is for this reason that the brand of film investigated, despite a low magnitude but highly significant variability is considered acceptable for general work. In between species comparisons the greatest gains in using the technique are likely to accrue by reducing the error component due to the calibration curve. Some indication of this improvement can be found in Table III, where regressions are based on selected observations. Thus E.M.S. is reduced by half for both the linear and curvilinear regressions and the L.S.D. consequently reduced.

To minimise the errors associated with the method, three procedures are recommended:

1. Samples should not be placed closer than 4 cm. to any edge of the x-ray film.
2. A number of step wedges should be placed on every film, and if excessive variation is

encountered, without correction for background variation, the negative should be discarded.
3. A calibration curve preferably should be prepared using wood of the same or a related species.

TABLE III The Least Significant Difference Between Two Estimates of Density

Regression*	Error Mean Square	Least Significant Difference (g./cc.)†
1. Linear (all observations) $Y = 0{\cdot}0735D + 0{\cdot}0638$	0·0013	0·055
2. Linear (selected observations) $Y = 0{\cdot}0679D + 0{\cdot}0964$	0·0006	0·039
3. Curvilinear (all observations) $Y = 00018D^2 + 0{\cdot}0439D + 0{\cdot}1660$	0·0010	0·049
4. Curvilinear (selected observations) $Y = 0{\cdot}0020D'' + 00388D + 0{\cdot}1879$	0·0005	0·036

Note:
*Y represents wood density, D optical density of the x-ray negative.
†L.S.D. $= [2(\sigma^2 \text{ optical density} + \text{Error Mean Square})]^{\frac{1}{2}} = [2(0{\cdot}012^2 + \text{Error Mean Square})]^{\frac{1}{2}}$

Influence of X-rays on the Cellulose Acetate Standards

One of the step wedges used in this work has been irradiated more than a hundred times, whereas the others have only been irradiated a few times. Despite this, no change has been observed.

Application of X-ray Densitometric Analysis

The proof of any new technique lies in its application; it should be flexible, accurate and not too time consuming. The authors believe that for within species studies the modified technique of X-ray densitometry fulfils all these requirements, and two examples are quoted.

(a) Hardwoods: Rudman and Higgs (in preparation) have made detailed within and between tree studies of density in *Eucalyptus regnans* F. v. Muell. One aspect of this work involved the calculation of weighted mean densities for discs at various heights and so the determination of the mean density for the tree. The data presented in Fig. 3 illustrates important phenotypic differences; only a single density determination was made for each position within each tree (approximately 50 positions per tree being examined) and for the relevant density standards.

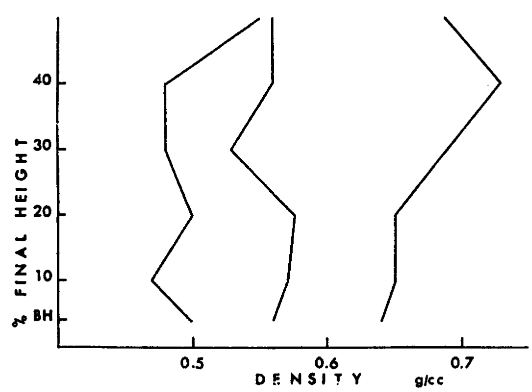

Figure 3 Variation with height of the wood density in trees of *Eucalyptus regnans*; each height is represented by the weighted disc density.

(b) Softwoods: The effects of potassium deficiency in *Pinus radiata* D. Don on wood density has been examined (Rudman and McKinnell, in preparation) and highly significant differences demonstrated between trees growing on sites fertilized with various levels of KCl. In this study each treatment level was represented by 18 trees, with seven outer growth rings per tree being examined. Single tracings of the growth ring density variations and density standards were made (Table IV). The variation in wood density between the plots before fertilization was not significant whereas in the period following treatment the least significant difference between plots was exceeded.

TABLE IV Effects of Nutrient Deficiency and Its Correction on Wood Density of *Pinus radiata*[1]

Year[2]	1959/60 & 1960/61	1961/62	1962/63	1963/64	1964/65	1965/66
Control	·413	·444	·468	·517	·533	·553
KCl, 9 cwt./ac.	·405NS	·405*	·402**	·458*	·460**	·510NS
L.S.D.[3] 5%	·027	·036	·038	·052	·049	·051
L.S.D. 1%	·037	·048	·052	·070	·067	·069

Notes:
(1) Trees planted in 1954,
(2) KCl applied in December 1960, hence the first year showing the effects of treatment is 1961/62.
(3) L.S.D. – least significant difference

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